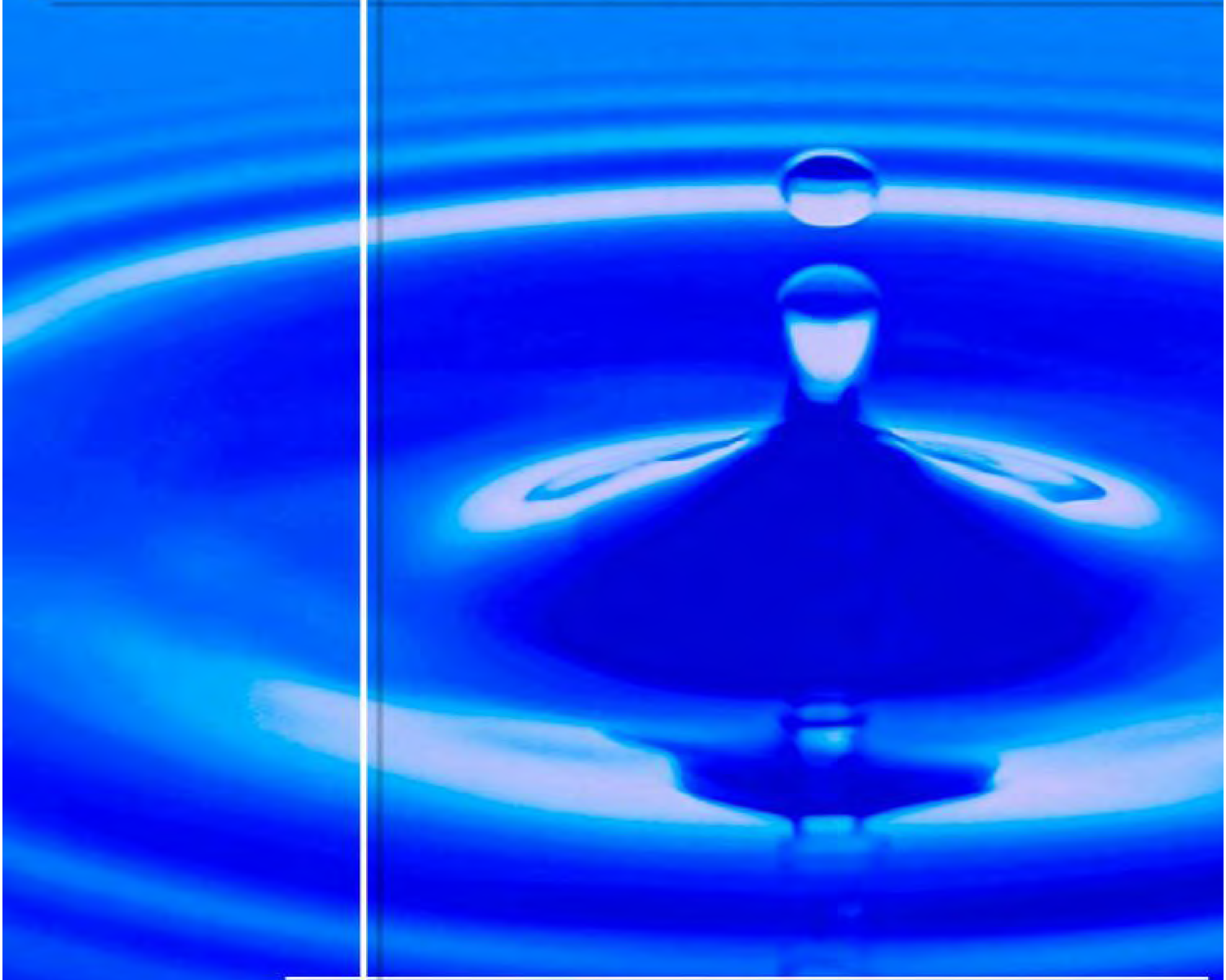
RIENCO
Consulting



FLOOD MODELLING REPORT

Macquarie Rivulet Below Sunnybank (Existing Conditions)

for Cardno Forbes Rigby

February 2011

DOCUMENT CONTROL

Report title:
FLOOD MODELLING REPORT
Macquarie Rivulet Below Sunnybank
(Existing Conditions)

Prepared for:
Cardno

Prepared by:
RIENCO CONSULTING
Water Engineering Specialists
PO Box 602 Sorell Tasmania 7172
ACN 000 960 850 ABN 14 000 960 850
Ph 0437 250 500
Email secretary@rienco.com.au

Version History

Version	Released	Status	Author	Reviewer	Approval
D0	29/11/2009	DRAFT Rev0	EHR	EHR	EHR
R0	18/12/2009	FINAL Rev0	EHR	EHR	EHR
R1	09/02/2010	FINAL Rev1	EHR	EHR	EHR
R2	18/02/2010	FINAL REV2	EHR	EHR	EHR
R3	25/02/2011	FINAL REV3	EHR	EHR	EHR
R4	14/03/2011	FINAL REV4	EHR	EHR	EHR

Issue History

Version	Issued	Copies	Format	Issued To	By
D0	29/11/2009	1	paper	Cardno Forbes Rigby	EHR
D0	29/11/2009	1	pdf	Cardno Forbes Rigby	EHR
R0	18/12/2009	1	paper	Cardno Forbes Rigby	EHR
R0	18/12/2009	1	pdf	Cardno Forbes Rigby	EHR
R1	09/02/2009	1	doc	Cardno Forbes Rigby	EHR
R2	18/02/2010	1	doc	Cardno Forbes Rigby	EHR
R3	25/02/2011	1	doc	Cardno	EHR
R4	14/03/2011	1	doc	Cardno	EHR

TABLE OF CONTENTS

DOCUMENT CONTROL I

TABLE OF CONTENTS III

LIST OF TABLES IV

LIST OF FIGURES V

LIST OF APPENDICES VII

ABBREVIATIONS IX

TECHNICAL TERMS X

EXECUTIVE SUMMARY XI

1 INTRODUCTION 1

1.1 REPORT BACKGROUND 1
1.2 MODELLING OBJECTIVES 1
1.3 MODELLING METHODOLOGY 2
1.4 MODELLING SCOPE 2
1.5 REPORT QUALIFICATIONS 3
1.6 CONCEPT PLAN MODIFICATION B2 3

2 THE CATCHMENT 5

2.1 GENERALLY 5
2.2 CLIMATE 6
2.3 PHYSIOGRAPHY 7
2.4 GEOLOGY SOILS & STREAM MORHOLOGY 9
2.5 SURFACE COVER AND LANDUSE 14
2.6 DRAINAGE CHARACTERISTICS 15

3 AVAILABLE DATA 18

3.1 GENERALLY 18
3.2 CATCHMENT MAPPING 18
3.3 AERIAL PHOTOGRAPHY 19
3.4 AERIAL SURVEY (ALS) 21
3.5 CREEK AND DRAINAGE STRUCTURES (SURVEY) 23
3.6 CREEK AND DRAINAGE STRUCTURES (PHOTOGRAPHY) 24
3.7 RAINFALL GAUGING 25
3.8 STREAM GAUGING 26
3.9 HISTORIC RAINFALL AND FLOODING 28
3.10 PREVIOUS STUDIES 33

4 HYDROLOGIC MODEL ESTABLISHMENT 37

4.1 MODEL SELECTION 37
4.2 MODEL CONSTRUCTION 37

5 HYDRAULIC MODEL ESTABLISHMENT 47

5.1 MODEL SELECTION 47
5.2 MODEL CONSTRUCTION 48

6 MODEL CALIBRATION AND VALIDATION 53

6.1 CALIBRATION & VALIDATION METHODOLOGY 53

6.2 CALIBRATION EVENT OF JUNE 1991 53
6.3 MODEL VALIDATION 59

7 DESIGN FLOOD ESTIMATION 60

7.1 DESIGN FLOODING CONSIDERATIONS 60
7.2 DESIGN FLOOD HYDROLOGY 65
7.3 DESIGN FLOOD HYDRAULICS 67

8 FLOOD BEHAVIOUR 70

8.1 GENERALLY 70
8.2 FLOOD HYDRAULICS 70
8.3 FLOOD HAZARD 70

9 ACKNOWLEDGMENTS 72

10 REFERENCES 73

LIST OF TABLES

TABLE 1.1 : CONCEPT PLAN APPROVAL MODIFICATION B2 3

TABLE 2.2: ANNUAL CLIMATE AVERAGE DATA FOR WOLLONGONG 7

TABLE 2.3.1 : CATCHMENT PHYSIOGRAPHY 8

TABLE 3.7 : RAINFALL GAUGES IN MACQUARIE RIVULET 25

TABLE 3.8.2 ALBION PARK GAUGES – PEAK GAUGING 26

TABLE 3.9.1: RAINFALL DATA REVIEWED FOR CURRENT STUDY 28

TABLE 4.2.2: ADOPTED IMPERVIOUS COVER LEVELS 39

TABLE 4.2.6 LOCATION AND DESCRIPTION OF DESIGN RAINFALL GAUGES 42

TABLE 4.2.7 HYDROLOGIC MODEL PARAMETERS 42

TABLE 6.2.3A: PEAK DISCHARGES AT SELECTED LOCATIONS –JUNE 1991EVENT 56

TABLE 6.2.3B: LIKELY ERROR IN LEVEL DUE TO POSITIONAL UNCERTAINTY 57

TABLE 7.1.3: BLOCKAGE LEVELS APPLIED TO THIS STUDY 62

TABLE 7.2.1 ADOPTED DESIGN HYDROLOGIC MODEL PARAMETERS 66

TABLE 7.2.2: SUMMARY OF DESIGN PEAK DISCHARGES AT SELECTED LOCATIONS 66

TABLE 7.3.3: DESIGN PEAK FLOOD LEVELS AT SELECTED LOCATIONS 68

LIST OF FIGURES

FIGURE 2.1: THE MACQUARIE RIVULET CATCHMENT 6

FIGURE 2.3.1: MACQUARIE RIVULET TOPOGRAPHY.......... 8

FIGURE 2.4.1: GEOLOGY OF THE MACQUARIE RIVULET CATCHMENT 10

FIGURE 2.4.2: SOIL TYPES IN THE MACQUARIE RIVULET CATCHMENT, HAZELTON (1992).......... 11

FIGURE 2.4.3: CHANGES IN DELTA FORM MACQUARIE RIVULET 14

FIGURE 2.5: SURFACE COVER & LAND USE (2005) 15

FIGURE 2.6.1: MACQUARIE RIVULET CATCHMENT STREAM NETWORK 16

FIGURE 3.3.1: AERIAL PHOTO OF ALBION PARK- CIRCA 1949 & JUNE 2004 19

FIGURE 3.3.2A: 2005 AERIAL PHOTOGRAPHY –TILE COVERAGE 20

FIGURE 3.3.2B: 2005 AERIAL PHOTOGRAPHY – SAMPLE SITE.......... 21

FIGURE 3.4.2: 2007 AIR-BORNE LASER SCANNING (ALS) TILE COVERAGE 22

FIGURE 3.4.3: 20075 AIR-BORNE LASER SCANNING (ALS) EXAMPLE 22

FIGURE 3.5.3: STRUCTURES REVIEWED.......... 24

FIGURE 3.7 : MACQUARIE RIVULET CATCHMENT GAUGES 25

FIGURE 3.8.2 : ALBION PARK CSR RATING CURVES.......... 27

FIGURE 2.12.3 : PRINCES HIGHWAY PROVISIONAL CSR RATING CURVE 28

FIGURE 4.2.1` : WBNM MODEL TOPOLOGY.......... 38

FIGURE 4.2.2A : HYDROLOGIC LAND USE CLASSES (2009).......... 39

FIGURE 4.2.2B: IMPERVIOUS COVER IN EACH SUB-AREA (2005) 40

FIGURE 4.2.5: AREAS OF ABNORMAL FLOODPLAIN STORAGE AND DIVERSIONS.......... 41

FIGURE 4.2.8A PEAK LOCAL UNIT DISCHARGE (M3/S/HA) 1% AEP EVENT 45

FIGURE 4.2.8B PEAK CUMULATIVE UNIT DISCHARGE (M3/S/HA) 1% AEP EVENT 46

FIGURE 5.2.1: MODEL GRID & ACTIVE ZONE EXTENTS 48

FIGURE 5.2.2 HYDRODYNAMIC MODEL ROUGHNESS ZONES(2009).......... 49

FIGURE 5.2.3: HYDRODYNAMIC MODEL TOPOGRAPHY 50

FIGURE 6.2.2A: HYETOGRAPH & IFD –MACQUARIE PASS - JUNE 1991 54

FIGURE 6.2.3B: ALBION PARK AND PRINCES HIGHWAY CSRS – JUNE 1991 55

FIGURE 6.2.3A : JUNE ‘91 DISCHARGE HYDROGRAPHS – SUNNYBANK & PRINCES HWAY CSRS .. 55

FIGURE 6.2.3B : JUNE ‘91 STAGE HYDROGRAPH –PRINCES HWAY CSR 57

FIGURE 6.2.3C : RECORDED –V- SIMULATED PEAK FLOOD LEVELS – JUNE 1991 58

FIGURE 7.1.4: LAKE ILLAWARRA AND MACQUARIE RIVULET 1%AEP HYDROGRAPHS 64

FIGURE 7.2.1: DESIGN EDS HYETOGRAPH & IFD AT DESIGN GAUGE “MACRIV#1” 65

FIGURE 7.1.4: SELECTED DESIGN LOCATIONS 68

LIST OF APPENDICES

A. THE CATCHMENT

A.1 LOCATION PLAN
A.2 TOPOGRAPHY
A.3 GEOLOGY
A.4 SOILS
A.5 COVER & LANDUSE
A.6 STREAM NETWORK
A.7 GAUGING

B. SUPPORTING DATA

B.1 AERIAL PHOTOGRAPHY
B.2 ALS SURVEY DATA
B.3 STREAM PHOTOGRAPHY
B.4 STRUCTURE SURVEY & PHOTOGRAPHY
B.5 JUNE 1991 RAINFALL HYETOGRAPHS
B.6 JUNE 1991 SUNNYBANK STAGE RECORD
B.7 JUNE 1991 PRINCES HIGHWAY STAGE RECORD
B.8 SUNNYBANK RATING CURVES
B.9 PRINCES HIGHWAY RATING CURVES
B.10 JUNE 1991 FLOOD PHOTOGRAPHY
B.11 JUNE 1991RECORDED FLOOD LEVELS

C. HYDROLOGIC MODEL ESTABLISHMENT

C.1 MODEL LAYOUT
C.2 MODEL IMPERVIOUS COVER
C.3 MODEL STORAGES & DIVERSIONS

D. HYDRODYNAMIC MODEL ESTABLISHMENT

D.1 MODEL PLAN EXTENTS
D.2 MODEL TOPOGRAPHY
D.3 MODELSURFACE ROUGHNESS
D.4 MODEL STRUCTURES
D.5 MODEL BOUNDARY CONDITIONS

E. MODEL CALIBRATION

E.1 RECORDED –V- MODELLED JUNE 91 HYDROGRAPH AT PH GAUGE
E.2 RECORDED –V- MODELLED JUNE 91 HYDROGRAPH AT SB GAUGE
E.3 RECORDED –V- MODELLED JUNE 91 PEAK FLOOD SURFACE
E.4 ADOPTED HYDROLOGIC PARAMETERS
E.5 ADOPTED SURFACE ROUGHNESS VALUES

F. DESIGN FLOOD HYDROLOGY

F.1 HYDROGRAPHS AT LOCATIONS OF INTEREST - 1%AEP EVENT
F.2 HYDROGRAPHS AT LOCATIONS OF INTEREST - PMF EVENT

G. DESIGN FLOOD HYDRAULICS

G.1 20% AEP PEAK ELEVATION FLOOD SURFACE
G.2 1% AEP PEAK ELEVATION FLOOD SURFACE
G.3 PMF PEAK ELEVATION FLOOD SURFACE
G.4 20% AEP PEAK VELOCITY FLOOD SURFACE
G.5 1% AEP PEAK VELOCITY FLOOD SURFACE
G.6 PMF PEAK VELOCITY FLOOD SURFACE
G.7 20% AEP PEAK DEPTH FLOOD SURFACE
G.8 1% AEP PEAK DEPTH FLOOD SURFACE
G.9 PMF PEAK DEPTH FLOOD SURFACE
G.10 20% AEP PEAK VXD FLOOD SURFACE

G.11 1% AEP PEAK VXD FLOOD SURFACE
G.12 PMF PEAK VXD FLOOD SURFACE
G.13 20% AEP PROV HYD HAZARD FLOOD SURFACE
G.14 1% AEP PROV HYD HAZARD FLOOD SURFACE
G.15 PMF PROV HYD HAZARD FLOOD SURFACE

ABBREVIATIONS

	Abbreviation Description
AEP	Annual Exceedance Probability; The probability of a rainfall or flood event of given magnitude being equalled or exceeded in any one year.
AHD	Australian Height Datum: National reference datum for level
ALS	Air-borne Laser Scanning; aerial survey technique used for definition of ground height
ARI	Average Recurrence Interval; The expected or average interval of time between exceedances of a rainfall or flood event of given magnitude.
AR&R	Australian Rainfall and Runoff; National Code of Practice for Drainage published by Institution of Engineers, Australia, 1987.
EDS	Embedded Design Storm; synthesised design storm involving embedment of an AR&R design burst within a second design burst of much longer duration
FPDM	Floodplain Development Manual; Guidelines for Development in Floodplains published by N.S.W. State Government, 2005.
FSL	Flood Surface Level;
GIS	Geographic Information Systems; A system of software and procedures designed to support management, manipulation, analysis and display of spatially referenced data.
IFD	Intensity-Frequency-Duration; parameters describing rainfall at a particular location.
ISG	Integrated Survey Grid; ISG: The rectangular co-ordinate system designed for integrated surveys in New South Wales. A Transverse Mercator projection with zones 2 degrees wide (Now largely replaced by the MGA).
LEP	Local Environment Plan; plan produced by Council defining areas where different development controls apply (e.g. residential vs industrial)
LGA	Local Government Area; political boundary area under management by a given local Council. Council jurisdiction broadly involves provision of services such as planning, recreational facilities, maintenance of local road infrastructure and services such as waste disposal.
MGA	Mapping Grid of Australia; This is a standard 6° Universal Transverse Mercator (UTM) projection and is now used by all states and territories across Australia.
MHI	Maximum Height Indicator; measuring equipment used to record flood levels
PMF	Probable Maximum Flood; Flood calculated to be the maximum physically possible.
PMP	Probable Maximum Precipitation; Rainfall calculated to be the maximum physically possible.
RCP	Reinforced Concrete Pipe;
km	Kilometre; (Distance = 1,000m)
m	Metre; (Basic unit of length)
m2	Square Metre; (Basic unit of area)
ha	Hectare; (Area =10,000 m2)
m3	Cubic Metre; (Basic unit of volume)
m/s	Metres/Second; (Velocity)
m3/s	Cubic Metre per Second; (Flowrate)
s	Second; (basic unit of time)
SCC	Shellharbour City Council; name of the Council with jurisdiction over the Shellharbour LGA

TECHNICAL TERMS

Term	Description
Alluvium	Material eroded, transported and deposited by streams.
Antecedent	Pre-existing (conditions e.g. wetness of soils).
Catchment	Area draining into a particular creek system, typically bounded by higher ground around its perimeter.
Critical Flow	Water flowing at a Froude No. of one.
Culvert	An enclosed conduit (typically pipe or box) that conveys stormwater below a road or embankment.
Discharge	The flowrate of water.
Escarpment	A cliff or steep slope, of some extent, generally separating two level or gently sloping areas.
Flood	A relatively high stream flow which overtops the stream banks.
Flood storages	Those parts of the flood plain important for the storage of floodwaters during the passage of a flood.
Floodways	Those areas where a significant volume of water flows during floods. They are often aligned with obvious naturally defined channels and are areas which, if partly blocked, would cause a significant redistribution of flow.
Flood Fringes	Those parts of the flood plain left after floodways and flood storages have been abstracted.
Froude No.	A measure of flow instability. Below a value of one, flow is tranquil and smooth, above one flow tends to be rough and undulating (as in rapids).
Geotechnical	Relating to Engineering and the materials of the earth's crust.
Gradient	Slope or rate of fall of land/pipe/stream.
Headwall	Wall constructed around inlet or outlet of a culvert.
Hydraulic	A term given to the study of water flow, as relates to the evaluation of flow depths, levels and velocities.
Hydrodynamic	The variation in water flow, depth, level and velocity with time
Hydrology	A term given to the study of the rainfall and runoff process.
Hydrograph	A graph of flood flow against time.
Hyetograph	A graph of rainfall intensity against time.
Isohyets	Lines joining points of equal rainfall on a plan.
Manning's n	A measure of channel or pipe roughness.
Orographic	Pertaining to changes in relief, mountains.
Orthophoto	Aerial photograph with contours, boundaries or grids added.
Pluviograph	An instrument which continuously records rain collected
Runoff	Water running off a catchment during a storm.
Scour	Rapid erosion of soil in the banks or bed of a creek, typically occurring in areas of high flow velocities and turbulence.
Siltation	The filling or raising up of the bed of a watercourse or channel by deposited silt.
Stratigraphy	The sequence of deposition of soils/rocks in layers.
Surcharge	Flow unable to enter a culvert or exiting from a pit as a result of inadequate capacity or overload.
Topography	The natural surface features of a region.
Urbanisation	The change in land usage from a natural to developed state.
Watercourse	A small stream or creek.

EXECUTIVE SUMMARY

Macquarie Rivulet is located partly in the Shellharbour City Council local government area and partly in the Wollongong City Council local government area, on the New South Wales coastal plain approximately 100 km to the south of the city of Sydney. The catchment is drained by two primary arms (Macquarie Rivulet and Marshall Mount Creek) and several secondary arms. The combined systems drain an area of approximately 107 km^2 of mixed forest, pasture and urbanised land, discharging into the south-western corner of Lake Illawarra. Flooding in Macquarie Rivulet and its tributaries is adversely affected at some locations by bridges, culverts and intrusions of development onto floodplains. Flooding in the outfall reach of Macquarie Rivulet is in addition affected by the level of flooding in Lake Illawarra.

Modelling was undertaken to quantify existing flood behaviour in the Macquarie Rivulet system in the general vicinity of the junction of Macquarie Rivulet and Marshall Mount Creek where a residential development is currently proposed. This modelling involved data collection, construction, calibration and validation of hydrologic and hydraulic models and determination of existing flood discharges and levels in the vicinity of the proposed development for the 5 Yr and 100Yr Average Recurrence Interval (ARI) events and the "Probable Maximum" design flood. It should be noted that this modelling specifically targeted flood behaviour in the vicinity of the proposed development area, in these events This study was not intended to and does not purport to provide information on flood behaviour outside of the study area.

Data collection included, aerial survey, creek and structure survey and the collection and collation of recorded rainfall, flood heights and lake level data for historic storms. Calibration of models was undertaken using the 11th June 1991 flood event, with a high level of correlation between recorded and simulated peak flood discharges and levels.

Using this calibration and allowing for changes occurring in the catchment between the June 1991 event, and the present, flood behaviour in the study area was then modelled for the 5%, 1% AEP and PMF design flood events. It is noted that this 'design' event modelling incorporated consideration of blockage but did not consider the impact of future climate changes – climate change and regional development impacts will be considered in a separate report.

This modelling quantified flood levels, velocities, depth, unit flow (conveyance) and provisional hydraulic hazard through and in the vicinity of the proposed development site. In a 1% event Macquarie Rivulet inundates most of the low lying land along the southern boundary of the site and Marshall Mount Creek inundates a substantial portion of the low lying land in the north eastern cornerf of the site making access to the higher flood free land in the central portion of the site difficult. In both zones of inundation substantial secondary overland flow paths are evident, flowing at considerable depth and velocity at the peak of a 1% AEP flood. These secondary flow paths tend to isolate higher land between the main and secondary floodways in the early stages of a flood only to inundate the isolated parcel as the flood rises (a relatively dangerous situation - to be addressed in any proposed development.) While the extent of inundated land does not vary greatly between the 1% AEP and PMF flood events, velocities and depths are much higher in a PMF event. In general, most inundated land presents a 'high' provisional hydraulic hazard to those occupying such land. Areas of low provisional hydraulic hazard are however present in both valleys, between the mainstream and secondary floodways and on steeper land on the side slopes of tributary streams, particularly on the southern face of the Marshall Mount valley in the vicinity of the western boundary of the site.

1 INTRODUCTION

1.1 REPORT BACKGROUND

A residential development is proposed on land lying within the catchment of Macquarie Rivulet. This proposed development spans across the boundary between the Shellharbour City LGA and the Wollongong City LGA and is located near Mount Johnston, upstream of the junction between Macquarie Rivulet and Marshall Mount Creek.

Since part of this land lies within the floodplain of Macquarie Rivulet and/or Marshall Mount Creek, a review of existing flood behaviour in the vicinity of the site was commissioned by the land owners to provide advice on the best means of accommodating this flooding while meeting the owners vision for the proposed development. Cardno Forbes Rigby (CFR) was commissioned to undertake this work. Since Rienco Consulting had previously built a hydrologic model of the catchment and hydrodynamic model of the lower reaches of Macquarie Rivulet, they were engaged by CFR to undertake the modelling required to quantify existing flood behaviour in the vicinity of the proposed development site.

The modelling work associated with CFR's advice to the land owners was to proceed in three stages;

1. Quantifying flood behaviour under existing climatic and catchment conditions

2. Quantifying flood behaviour associated with the development as described in the overall concept plan, under future climatic and catchment conditions

3. As development progresses – Quantifying by more detailed modelling, flood behaviour associated with each development stage

This current report documents modelling work undertaken in the first stage, quantifying flood behaviour in the vicinity of the proposed development, under existing climatic and catchment conditions.

1.2 MODELLING OBJECTIVES

The primary objective of this present study is to develop a reliable and quantified understanding of existing flood behaviour in the vicinity of the proposed development.

This in turn leads to a number of secondary objectives including:

- The collection and collation of a reliable body of data on the physical characteristics of the catchment and study area

- The collection and collation of a reliable body of data on historic storms and flooding in the catchment and study area

- The establishment of well calibrated and validated hydrologic and hydraulic models of the catchment and study area

- The determination of flooding characteristics in terms of flood extents, flood levels, flow depths and flow velocities for the 5%, 1% Annual Exceedence Probability (AEP) and Probable Maximum Flood (PMF) events, in the vicinity of the proposed development site.

1.3 MODELLING METHODOLOGY

The study methodology adopted to meet the above objectives, includes a series of sequential tasks as summarised below:

- Collection and collation of data describing the physical characteristics of the catchment and study area.
- Collection and collation of data describing historic rainfall and flooding in the catchment and study area.
- Collection and collation of data describing the temporal and spatial characteristics of (design) rainfall of a given probability, across the catchment .
- Construction of hydrologic and hydrodynamic models of the catchment and study area.
- Calibration and validation of the hydrologic and hydrodynamic models
- Application of the calibrated models to establish (design) flood behaviour in a 5%, 1% and PMF flood event, within the study area under existing climatic and catchment conditions.

1.4 MODELLING SCOPE

This study is limited to the modelling of historic and design flood events in the general vicinity of and downstream of the proposed development, This study area is indicated on the Overall Catchment Plan (**Appendix A.1**).

The study area includes:

- The floodplain of Marshall Mount Creek from Marshall Mount Road down to the creeks junction with Macquarie Rivulet

- The floodplain of Macquarie Rivulet from Sunnybank down to the Marshall Mount Creek junction

- The floodplain of the combined Macquarie Rivulet and Marshall Mount Creek systems from the junction of Macquarie Rivulet with Marshall Mount Creek down to the Princes Highway Road Bridge

- The floodplain of Macquarie Rivulet from the Princes Highway road bridge down to and including its outfall into Lake Illawarra

Assessment of design event flooding has been carried out based on climate and catchment conditions as existing in 2009. Design event flooding in the general vicinity and downstream of the proposed development site has been quantified for the following flood events:

- 5 Year ARI (~20% AEP) flood event
- 100 year ARI (~1% AEP) flood event
- PMF (~1x 10^{-7} AEP) flood event

For each of these design events, flood surfaces have been calculated to reflect the blockage scenarios adopted by Shellharbour City Council in the Horsley Creek Flood Study with blockages and diversion spatially adjusted to incorporate all likely scenarios. These flood surfaces have been used to identify and describe flood behaviour within the study area.

1.5 REPORT QUALIFICATIONS

Information presented in this report has been developed to address the modelling objectives set out above. This report is not and does not purport to be a report on flood behaviour outside of the nominated study area.

1.6 CONCEPT PLAN MODIFICATION B2

This Flood Study (Revision 2) was submitted to the Department of Planning and a Concept Plan approval was granted on 8 December 2010, subject to the modifications set out in Schedule 2 of the Concept Plan approval. This Flood Study was updated (to Revision 3) in March 2011 to address all of the relevant requirements of Schedule 2, Modification B2.

Schedule 2, Condition B2 has been reproduced in Table 1.1 below, together with commentary on how the modifications have been addressed and which section of this report the supporting information can be found.

Table 1.1 : Concept Plan Approval Modification B2

Modification B2	**Description of how this modification has been addressed, and the section of this Report where compliance is confirmed**
Deletion of the eastern most fill area located between Macquarie Rivulet and Illawarra Highway. The bulk earthworks strategy in the Flood Mitigation Plan shall be amended accordingly	This study is limited to the investigation of existing flood behaviour and as such, this modification would be addressed in the FPRMS (Cardno, 2011).
Finer representation of minor tributaries	We understand this modification would be addressed in the FPRMS (Cardno, 2011).
An appropriate range of storm durations for the 20% AEP, 1% AEP, and PMF events.	The 20% AEP (5 yr ARI) was not previously included in this report as only the 1% AEP and PMF events are of relevance when determining flood constraints and development controls. Nonetheless, we have updated the modelling and reporting to include an assessment of the 20% AEP. Refer to Section 7.3.3 of this report. Further discussion on the appropriate range of storm durations has also been provided in Section 7.2.1 of this report.

Sensitivity analysis addressing variations in lake level and entrance conditions in Lake Illawarra	This study is limited to the investigation of existing flood behaviour and as such, this modification would be addressed in the FPRMS (Cardno, 2011).
Existing climate conditions and climate change having regard to DECCW's Draft Flood Rick Management Guide: Incorporating sea level rise benchmarks in flood risk assessments (October 2009) in the assessment of climate change conditions	This study is limited to the investigation of existing flood behaviour and as such, this modification would be addressed in the FPRMS (Cardno, 2011).
Compendium of rainfall, streamflow and topographic data and historic flood levels and behaviour for Macquarie Rivulet.	We understand compendium of data will be issued under separate cover.

2 THE CATCHMENT

2.1 GENERALLY

The catchment of Macquarie Rivulet lies within the Lake Illawarra sub-basin of the Wollongong Coastal Basin (214). It drains 107km2 of mostly forested and rural lands and is located some 100km to the south of Sydney on a thin band of coastal land between the Illawarra escarpment and the Tasman Sea. Macquarie Rivulet has its headwaters on the escarpment near Robinson, flowing east over the escarpment, to ultimately discharge into Lake Illawarra.

Adjoining catchments within the Wollongong coastal basin include, Duck Creek to the north, Horsley and Rocklow Creeks to the south east and Minnamurra River to the south

The drainage network of Macquarie Rivulet comprises three main arms:

- Macquarie Rivulet (The main arm draining the central portion of the catchment)
- Frazers Creek (A secondary arm draining the south-eastern sector)
- Marshall Mount Creek (A major arm draining the northern sector)

All three arms combine on the flood plain above the Princes Highway, to the immediate west of Albion Park airport. In large events, flows merge across the full width of the flood plain at this location to form a single near level pool of floodwater.

All three sub-catchments are predominantly rural with some existing urban development in the lower reaches of Frazers Creek and Macquarie Rivulet, around Albion Park. Areas to the west and south west of Albion Park are at present undergoing significant urban development.

Hazelton , Cooback and Yellow Rock Creeks are tributaries of Macquarie Rivulet, draining an area of mostly rural land to the south of the Illawarra Highway. Two heavily modified creeks, identified for the purposes of this study as Town and Tara Creeks, drain the built up area of Albion Park village into Frazers Creek.

The location and extents of the catchment, with respect to adjacent catchments and Lake Illawarra, is shown in Fig 2.1 and reproduced at a larger scale in **Appendix A1**.

The Lake Illawarra Flood Study (Lawson & Treloar, 2001) indicates the lakes catchment is some 270 km^2, accordingly, Macquarie Rivulet at 107 km^2, represent a significant proportion of the Lake's total catchment.

Figure 2.1: The Macquarie Rivulet Catchment

2.2 CLIMATE

The prevailing climate for the Macquarie Rivulet catchment is typical of other Illawarra catchments, being temperate with mild winters and only limited tropical (monsoonal) influences.

High rainfall intensity can be experienced due to the catchments proximity to the ocean (source of humidity) and the Illawarra escarpment (which enhances the amount of precipitation through an orographic rainfall effect). On an average annual basis, the area receives approximately 1300 mm of rainfall, with higher rainfall during the late summer and autumn months. Annual climate average data for southern Illawarra is summarised in Table 2.2. More detailed climate information is available from the Bureau of Meteorology's web site www.bom.gov.au.

When intense rainfall occurs, it generally occurs as a burst within a longer, less intense parent storm. These parent storms often occur in an episodic fashion in accordance with macro-climatic patterns of 'la nina'. During la nina episodes the probability of several large storms occurring in close succession is high. The most common climatic mechanism is a 'blocking pair' high and low pressure system producing moist onshore winds. These winds transport moisture laden air onshore. The moisture precipitates as the air cools when it passes up and over the escarpment. The episodic nature of rainfall in the catchment can result in high antecedent soil moisture levels for rainfall events occurring in the latter part of any rainfall phase.

Table 2.2: Annual Climate Average Data for Wollongong

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean daily max temp deg C	24.1	24.4	24.1	22.4	19.4	17.5	16.7	17.3	19.2	20.7	22.4	23.4	20.9
Mean 9am rel' humidity %	77	78	75	70	67	67	63	61	61	66	68	74	69
Mean 9am wind speed km/h	17	16	15	15	17	17	18	19	19	20	20	18	17
Mean monthly rainfall mm	116	158	184	93	89	140	63	88	55	108	94	90	1277
Mean no. of raindays	12	13	13	9	8	10	7	10	8	11	11	11	123
Highest monthly rainfall mm	351	575	529	350	421	465	220	286	189	424	600	366	-
Lowest monthly rainfall mm	19	5	16	14	1	0	0	6	4	8	12	11	-
Highest recorded daily rainfall mm	112	278	315	93	146	153	153	137	98	192	189	125	315
Mean no. of clear days	8	6	8	10	11	9	13	12	11	8	8	7	111

Source: BOM Port Kembla gauge

2.3 PHYSIOGRAPHY

2.3.1 PHYSIOGRAPHY

The Macquarie Rivulet catchment falls within a tapering wedge of coastal land confined to the east by the Tasman Sea and to the west by the Illawarra coastal escarpment. The width of this coastal belt of land is near zero at Stanwell Park some 40km to the north of Macquarie Rivulet, increasing to around 15 km in the vicinity of the Macquarie Rivulet at Shellharbour. At Kiama, to the immediate south of Macquarie Rivulet, the Illawarra escarpment runs down to the sea, severing this coastal belt of land.

Runoff from the foothills and escarpment has over the years created a series of primary spurs, running roughly east-west, from the escarpment down to the sea. Multiple lateral spurs have in turn developed on the primary spurs, running typically north-south. This pattern is readily evident on topographic maps of the area, the southern boundary of the catchment being a good example of this process. The topography of the catchment (represented by colour filled contours) is reproduced in Figure 2.3.1. and at a larger scale in **Appendix A2**.

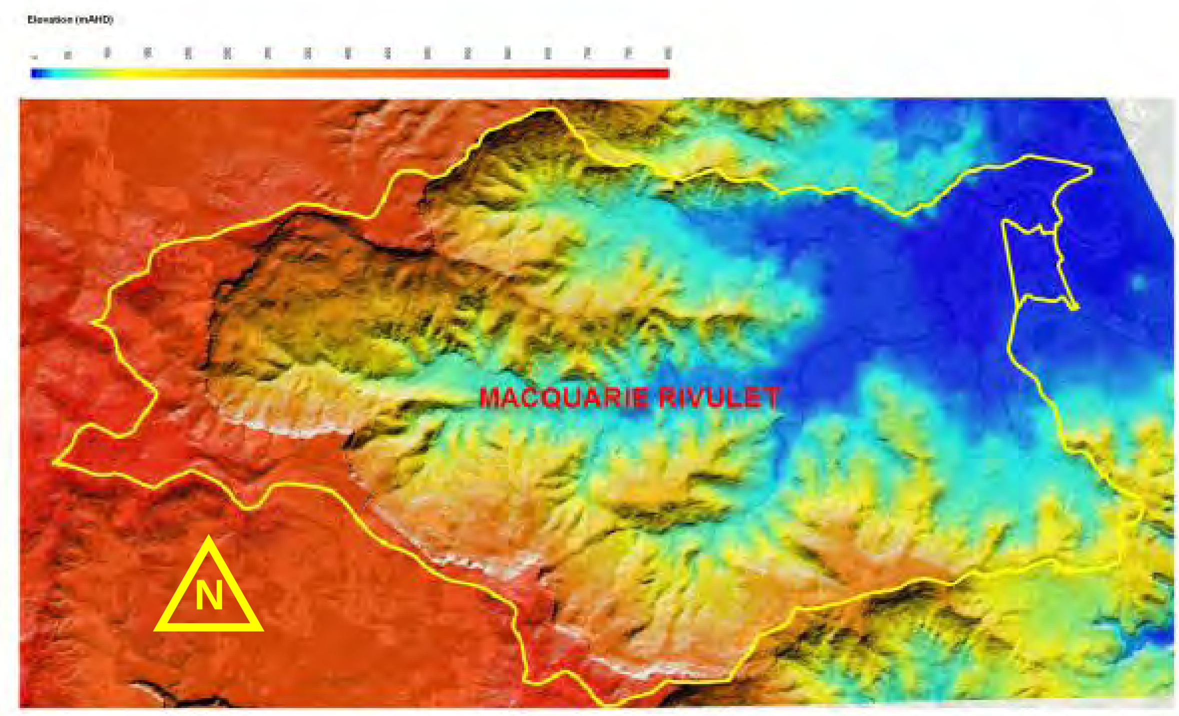


Figure 2.3.1: Macquarie Rivulet Topography

Macquarie Rivulet has a stream length of 22.5 km, with total fall from head waters to outlet of 680 metres. The Rivulet's equivalent mainstream slope is 8.4 m/km. The upper reaches are quite steep producing some spectacular water falls down the escarpment. For the majority of its length, the stream meanders along a relatively flat river valley with the lower reaches combining on a broad flat flood plain, above the Princes Highway. The combined streams then discharge into Lake Illawarra, where silt deposition has formed a pronounced delta.

Physiographic parameters for the catchment of Macquarie Rivulet as a whole, and its main sub-catchments are set out in Table 2.3.1.

Table 2.3.1 : Catchment Physiography

Catchment (Subcatchment)	**Macquarie Rivulet Overall**	**Macquarie Rivulet to Sunnybank**	**Yellow Rock Creek**	**Marshall Mt Creek**	**Frazers Creek**
Linear Parameters					
Mainstream Order	5	5	4	5	4
Mainstream Length (km)	22.5	11.9	8.5	10.8	10.0
Basin Length (km)	15.6	9.0	6.5	9.5	6.7
Meander Index	1.4	1.3	1.5	1.1	1.5

Bifurcation Ratio (Avg)	4.0	4.0	4.0	4.5	-
Overland Flow Length (Avgm)	100	-	-	-	-
Areal Parameters					
Basin Area (km^2)	105.2	35.0	17.0	20.2	13.8
Basin Shape (form factor)	0.43	0.43	0.56	0.18	0.31
Drainage Density (km^{-1})	3.2	2.8	3.0	3.9	3.1
Stream Frequency	5.0	4.2	4.3	7.2	4.1
Relief Parameters					
Weighted Mainstream Slope	0.016	0.04	0.04	0.01	0.01
Avg Valley Side Slopes	0.25	0.3	0.2	0.2	0.05
Mean Elevation (m)	300	350	260	140	90
Basin Relief (m)	770	760	710	600	350
Ruggedness No.	2.5	2.3	2.1	2.3	1.1
Geometry No.	10	7.6	10.6	11.7	21.6

Source: WRF report on Macquarie Rivulet as a Reference Catchment (1986)

As is apparent from the above, all sub-catchments are somewhat elongated (Marshall Mount Creek in particular) but with the exception of Frazers Creek are topographically similar. Frazers Creek stands out as a much flatter and lower relief sub-catchment than the other sub-catchments of the Macquarie Rivulet system.

2.4 GEOLOGY SOILS & STREAM MORHOLOGY

2.4.1 GEOLOGY

The stratigraphy of the catchment generally comprises Triassic age, Narrabeen Group sandstone and siltstone (cliffs), overlying Permian age Illawarra Coal Measures (base of cliffs) with talus foothill slopes (mixture of the above). These in turn run down to residual soils and clays overlying a Permian age Shoalhaven Group, Kiama tuff basement. Quaternary deposits of alluvium, sands and silts are present on flood plains and in swamps.

Throughout the Illawarra, this coastal wedge has a similar east-west profile, with the high (600 metre) escarpment to the west, falling sharply to around the 450 metre contour level, at which point the talus slopes commence. These slopes in turn run down at a 15 to 35% grade to around the 100 metre contour level, where residual soils and clays are encountered. In the residual soil/clay zone, surface slopes are typically in the 5 to 15% range.

At around the 4 metre contour level, the profile again changes, to an overburden of recently transported sediments deposited on a relatively flat grade.

A simplified geological plan of the catchment is reproduced in Figure 2.4.1 and at a larger scale in **Appendix A3**. A more detailed description of the geology of the area is provided by Bowman (1966)   In the records of the Geological Survey of NSW Vol 14, part 2 and on 1:250,000 mapping by the NSW Department of Mines (sheet Wollongong 5I-56-9).

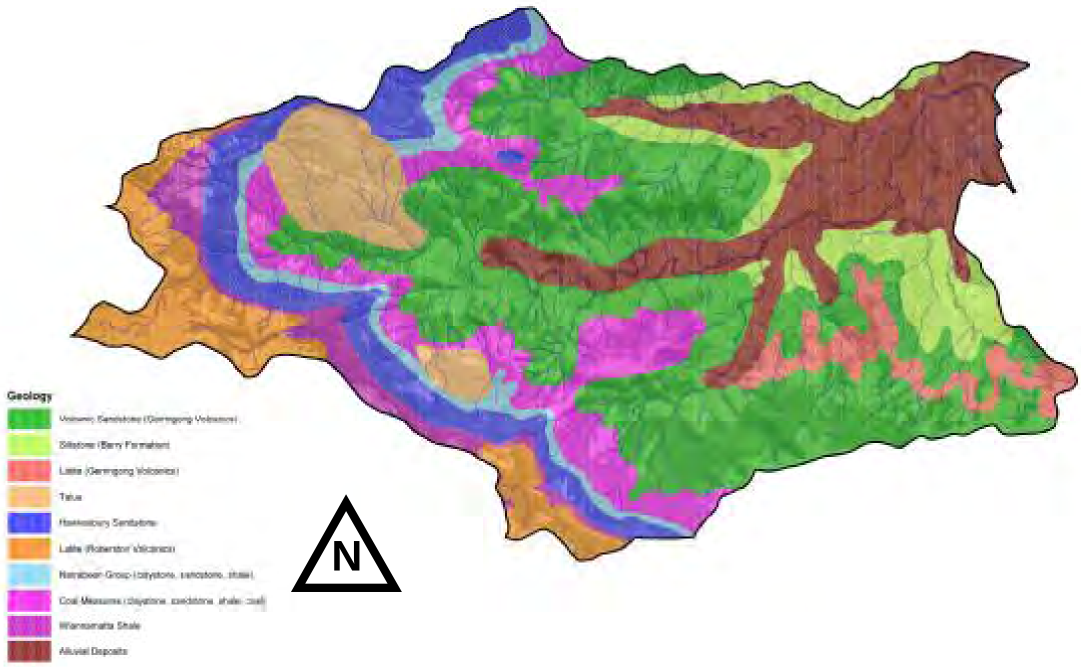


Figure 2.4.1: Geology of the Macquarie Rivulet Catchment

2.4.2 SOILS

The distribution and characteristics of soils within the catchment is described by Hazelton (1992) in Soil Landscapes of the Kiama Region prepared for the Department of Conservation and Land Management (NSW) and on the 1:100,000 CaLM Soil Landscape series (sheet 9028). A GIS compatible version of the data was obtained from the Department of Natural Resources and an extract included in Figure 2.4.2 (with catchment extent and photo underlay subsequently added). A larger scale version is reproduced in **Appendix A4.**

The soil descriptions provided by Hazelton are generic descriptions that apply across the coverage of each map sheet.

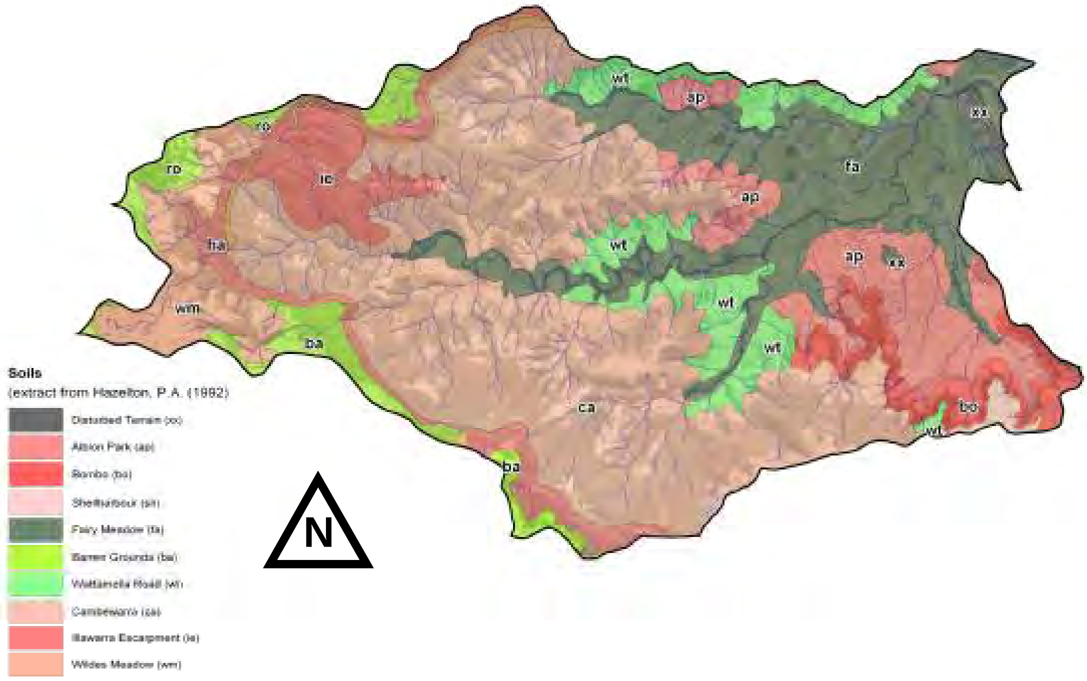


Figure 2.4.2: Soil Types in the Macquarie Rivulet Catchment, Hazelton (1992)

There are several soil types within the Macquarie Rivulet catchment identified in this mapping: Soil type in the catchment is however dominated by five soil types;

- Cambewarra (ca) soils in the foothills.
- Wattomolla Rd (wt) soils at the base of the foothills
- Fairy Meadow (fa) soils on the valley floor
- Albion Park (ap) soils in Albion Park and
- Disturbed (xx) soils in the far eastern section toward the catchment outlet.

These soils are described by Hazelton as;

1) Cambewarra (ca): This soil is described as being located on steep to very steep hills with broad colluvial benches on latite. Surface slopes are typically > 30%. The soil is relatively deep (>150mm) and is noted as having low water holding capacity.

2) Wattamolla Rd (wt): This soil is described as being located on long, gently to moderately inclined side slopes and undulating to rolling hills at slopes of between 5 and 15%. The soil is moderately deep (50-100mm) and is noted as being hard setting with a high organic content.

3) Fairy Meadow (fa): This soils is described as occurring on alluvial plains, floodplains and valley flats at slopes of between 5 and 10%. The soil is moderately deep (50-100cm)

and noted to have a high permeability (high infiltration capacity), however high seasonal water tables can occur which would limit infiltration volumes.

4) Albion Park (ap): This soil is described as being located on short steep upper slopes with long gentle foot slopes. The soil is moderately deep (50-100cm) and is described as having limitations of waterlogging, seasonally high water table and a high available water holding capacity (amongst others). These limitations are all indicative of a clay based soil with limited infiltration capacity.

5) Disturbed Terrain (xx): Soils that have been highly disturbed by human activity. Within Macquarie Rivulet these include areas of substantial earthworks at locations such as Haywards bay, Macquarie Shores and at the Airport.

With respect to the hydrological properties of these catchment soils, the clay based soils, which dominate the catchment valley side slopes, permit only limited infiltration of runoff. during a storm event. There are however significant areas of deep loamy soils on the valley floor which do have the ability to absorb considerable runoff in the early stages of an event. The magnitude of this initial infiltration (loss) will however depend greatly on the extent to which these soils have been pre-saturated by earlier rainfall. The presence or otherwise of lead up rainfall prior to a modelled event is therefore likely to be a significant factor in setting initial losses in this catchment.

The Soil Hydrological Properties of Australia database produced by CRC for Catchment Hydrology was also investigated, however the data was found to be too coarse for application to this study.

2.4.3 STREAM MORPHOLOGY

The catchment of Macquarie Rivulet site is drained by two characteristically different stream types. These are large perennial streams such as Macquarie Rivulet and Marshall Mount Creek running in the valley floor and numerous smaller mostly ephemeral streams (often unnamed), draining the valley sides.

The two large perennial streams convey runoff from contributory catchments (upstream of the Macquarie Rivulet – Marshall Mount Creek junction) of $86Km^2$ and $19Km^2$ respectively. They retain the general characteristics of a natural stream, with well-defined bed and banks, permanent pools, remnant riparian vegetation and alluvial terraces defining the extent of historic channel migration. While this migration is generally slow, large episodic changes have been observed following large flood events occurring within the period of European settlement.

Both of the larger systems display the characteristic meander patterns of a large stream flowing through a semi-confined valley. These meanders indicate that these reaches are performing a sediment transfer function (i.e. transferring bed load materials along the channel in an efficient manner.

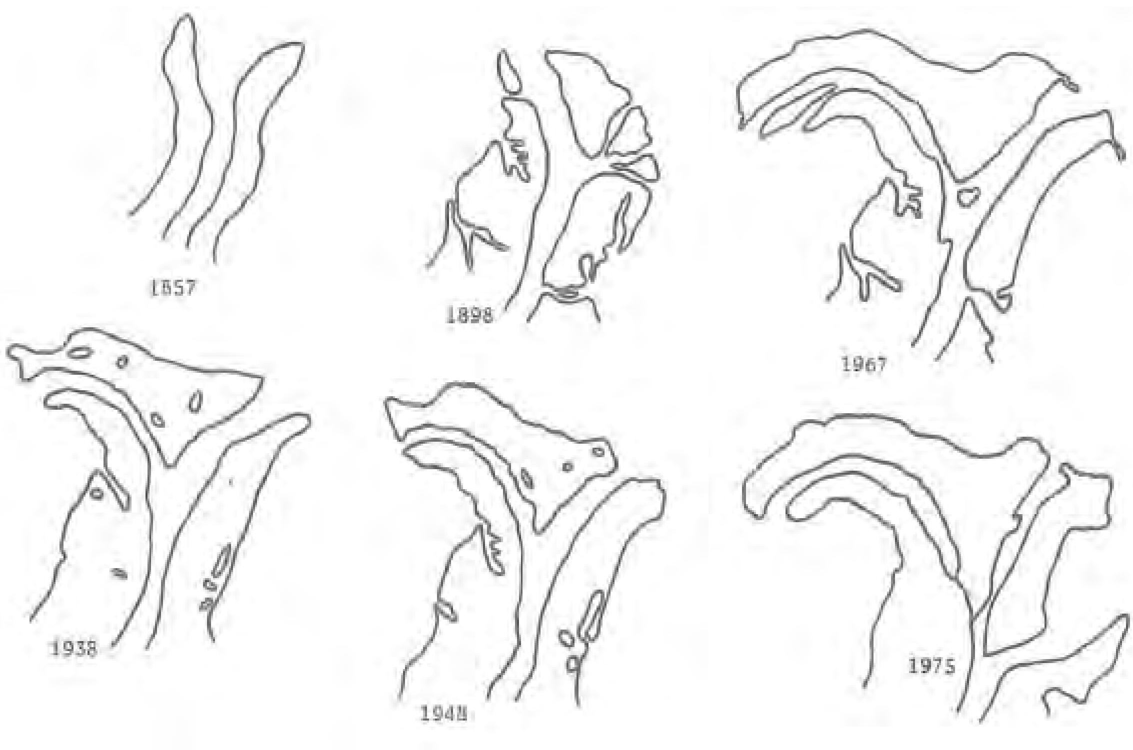
The application of an idealised fluvial system model may not however be appropriate for the rivulet which also displays the characteristics of an osage stream (much larger meanders than would ordinarily be expected for such a relatively small river). In a study undertaken by Neller (1976), it is suggested that this geometry possibly reflects the morphological impact of rare flood events. This is thought to be a localised escarpment based phenomenon, whereby orographic uplift induces exceptionally intense rainfall bursts Channel geometry in turn develops in response to these episodic events with a greater bank full flow capacity than is found elsewhere in streams with comparable catchment area.

Both these larger streams have coarse bed sediments (sands and gravels), with very few exposures of bedrock indicating that they intersect a broad alluvial stratigraphy. Previous soil sampling (Huang *et al*, 1996), found that soil taken from the lower part of the banks in Marshall Mount Creek typically has high clay content. This provides a competent and resilient bank material, which supports near vertical banks.

The stability of the existing large streams also reflects the presence of remnant vegetation along the banks. The presence of vegetation has been found to be another dominant factor influencing channel geometry (Huang *et al*, 1996).

The smaller streams feeding into Macquarie Rivulet are highly modified from their natural condition, having poorly defined and in places heavily altered morphology as a consequence of past and present agricultural practices. Significant clearing activity has also meant that there is now very little or no remnant riparian vegetation in or along the banks of these streams. These smaller systems have very little permanent water except where they intersect the groundwater profile. Evidence of bed lowering induced by increased flowrates following removal of vegetation from the catchment is observed in several places. This bed lowering is exacerbated by the relatively steep bed grades where these small streams flow down the valley sides. The bed and banks where evident are often lined with pasture grasses (in contrast to the larger systems, which have exposed bed sediments).

Observations made of the rapid expansion and then stabilisation of the Macquarie Rivulet delta; confirm that massive sediment loads were transported from the catchment over the early period of European settlement (see **Figure 4**). The rate of erosion is now reaching an equilibrium (i.e. channel geomorphology has changed in response to the change in hydrology brought about by catchment clearing). Whilst sediment transport will always continue, its rate will diminish unless new changes occur within the catchment.



Source: Illawarra Lake: Environmental Assessment Project (Univ' of Wollongong, 1976)

Figure 2.4.3: Changes in Delta Form Macquarie Rivulet

2.5 SURFACE COVER AND LANDUSE

The early Illawarra escarpment and foothills supported a cover of dense sub-tropical rainforest. The first major impact on vegetation and land use arose in the early 1800's with felling of the cedar trees. This was in turn followed in the mid 1800's by the clearing of the less dense stands of Blackbutt and Turpentine, on the flatter land, for pasture. Beyond the urban (ever increasing) limits of the village of Albion Park there has been little change in land usage for over 100 years, most of the land around the village having been used as pastoral land since first being cleared in the mid to late 1800's.

In 1843 a road was built connecting Shellharbour with Jamberoo. A bridge was constructed over Macquarie Rivulet in 1858, which together with a punt across Minnamurra River, upgraded access from Shellharbour to the north. In 1909 the original bridge over Macquarie Rivulet was replaced and in 1932 the Princes highway was constructed between Macquarie Rivulet and the Minnamurra River. The Princes Highway road bridge was again replaced in 1971 with a concrete structure and the crossing duplicated to provide multi lane access in 1990.

In 1887 the Illawarra Rail line was opened and in 1920 the original `Albion Park' station (then located at Yallah) relocated to Albion Park Rail, forming the nucleus of the village of Albion Park Rail. The existing timber rail bridge over Macquarie Rivulet was replaced in 1982 with a new concrete structure.

The aerodrome at Albion Park was opened in 1941.

In 1972, an industrial estate was created on land to the south of Macquarie Rivulet, between the Princes Highway and Illawarra Rail line.

In the late seventies and early eighties, a series of ash ponds were constructed at Tallawarra power station, infilling part of the flood plain between Macquarie Rivulet and Duck Creek. Wollingurry Creek was diverted to flow around the south eastern corner of these ponds, at this time.

During 1996 a coal washery discard fill emplacement commenced on the northern floodplain of Macquarie Rivulet, downstream of the rail bridge, part of earthworks for a residential subdivision (Haywards Bay) to be constructed at this location. At about the same time, Koona Street was extended north over Albion Creek to service a new subdivision (Macquarie Shores) on land east of the railway line and to the immediate south of Macquarie Rivulet.

Over the last decade, considerable new residential development has occurred around the village of Albion Park. This remains an area of ongoing development. Most recently a new residential development has occurred at Tullimbar, on the western perimeter of Albion Park village.

Residential, commercial and light industrial developments are generally located in the downstream (eastern) portion of the catchment with pasture in the central portion and remnant forest in the upstream (western) portion of the catchment. A graphic of the spatial distribution of the various surfaces as existing in aerial photography flown in 2005 is reproduced in Figure 2.5 and at a larger scale in **Appendix A5**

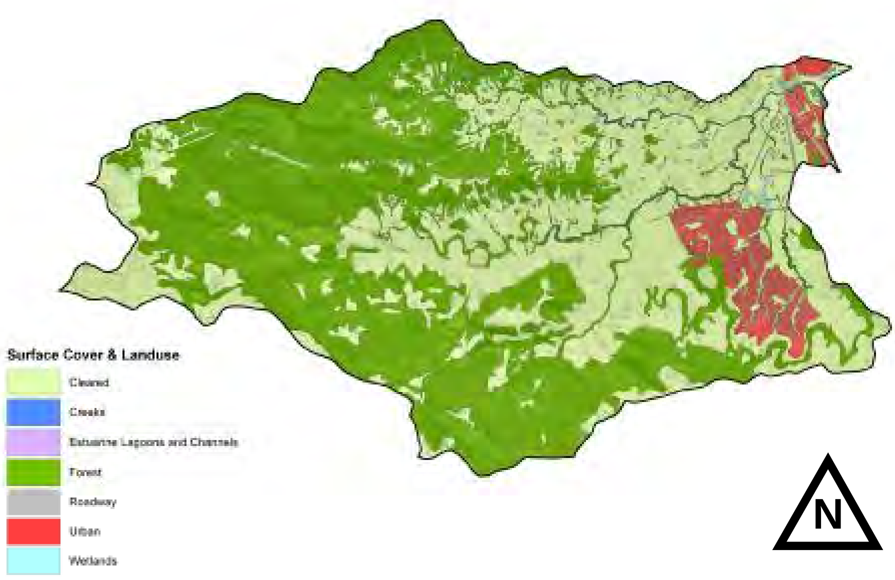


Figure 2.5: Surface Cover & Land Use (2005)

2.6 DRAINAGE CHARACTERISTICS

2.6.1 STREAM NETWORK

The Macquarie Rivulet catchment is drained by several major streams that meet on the floodplain above the Princes Highway road bridge, before discharging into Lake Illawarra.

The major streams include;

- Macquarie Rivulet
- Marshall Mount Creek and
- Frazers Creek (West and East arms)

Several smaller streams of relevance to the study include;

- Town and Tara Creeks Creeks (named to facilitate reference in this report)
- Cooback & Hazelton Creeks
- Yellow Rock Creek
- While not within the catchment, Albion Creek (as a stream potentially likely to receive diverted flow from Macquarie Rivulet in larger events).

Of the above, only Macquarie Rivulet and Marshall Mount Creek remain in a relatively natural condition and even these streams have been impacted over the years by clearing of vegetation from their banks to facilitate stock access.

Frazers, Town and Hazleton/Cooback Creeks have all been significantly altered as a consequence of urbanisation. Flow in these systems is impacted by a number of retarding basins, underground pipe systems and road culverts as well as changes to their plan form and bed profile.

These location of these streams are shown on the Stream Network plan included as **Appendix A.6** and reproduced in Figure 2.6.1 below.

Figure 2.6.1: Macquarie Rivulet Catchment Stream Network

Photography of the various streams, culverts and bridge structures, within the study area, is provided in **Appendices B3 and B4**.

Streams within the catchment have a highly variable flow regime with limited base flow, some being entirely ephemeral. Flowrates can rise rapidly following periods of intense rainfall however these conditions last for short periods only (hours).

The proximity and elevation of Lake Illawarra with respect to the lower reaches of Macquarie Rivulet results in a significant length of the lower reach of Macquarie Rivulet containing permanent water. A weir, constructed by a local farmer (Mr McDonald) in Macquarie Rivulet in 1966 to isolate fresh water from the brackish water of the Lake, acts as the terminus for this permanent backwater. The Lake has a mean water surface elevation of 0.3 m AHD. However, as identified in the Lake Illawarra Flood Study (Lawson & Treloar, 2001), flood levels in the lake can rise to as much as 3.2 m AHD under extreme (PMF) conditions. This would result in significant flooding of parts of the lower Maquarie Rivulet catchment even if no flow was occurring at that time within the main creek channels.

It is noted that the level of water stored in Lake Illawarra is largely isolated from the diurnal impact of oceanic tides. Tidal conditions are therefore not a consideration in assessing flooding in the Macquarie Rivulet catchment. Interactions between the water surface in the lake and flood discharges in Macquarie Rivulet are however a significant feature of flooding in the lower reaches of catchment.

The Macquarie Rivulet catchment adjoins several major catchments. It is topographically isolated from all of these with the exception of Albion Creek to the east. Earlier studies have raised the possibility that flood levels in Macquarie Rivulet could rise sufficiently in a major event to overtop the Albion Park Airport runway creating major inflow into the headwaters of Albion Creek. As an assessment of this diversion is needed to properly reflect flood behaviour in the study area, it has been included in this study.

3 AVAILABLE DATA

3.1 GENERALLY

Data previously available or collected in support of this study, that has been reviewed or used more directly in this study, included the following material in so far as it relates to the Macquarie Rivulet catchment.;

- Topographic Mapping
- Geological Mapping
- Soils Mapping
- Riparian Zone Mapping
- Cadastral and Zoning Mapping
- Aerial Photography
- ALS Survey Data
- Field Survey Data
- Creek and Structure Photography
- Rainfall and Stream Gauging Data
- Reports and Records of Historic Rainfall and Flooding
- Previous Studies and Reports

Several of these datasets have been discussed in the previous Section 2 describing 'The Catchment'. The remainder are discussed in the following.

3.2 CATCHMENT MAPPING

3.2.1 TOPOGRAPHY

Two metre contour topographic mapping of the catchment is available based on the 2 metre contour data set available from the NSW Department of Lands. This data is similar to the contour information used in the Department's standard 1:10,000 scale orthophoto mapping.

Whilst this data was available, it was used only in the very early stages of development of the study, principally in support of survey brief development for ground survey. More detailed Air-borne Laser Scanning (ALS) survey was used as the primary source of topographic data for the balance of the study including development of hydrologic and hydraulic models. This ALS dataset is separately described in **Section 3.3**.

3.2.2 CADASTRE AND ZONING

In order assist with the assessment of the spatial distribution of landuse and assist with estimation of impervious surface cover (described in **Section 4**), cadastre and zonings contained within SCC's Local Environmental Plan 2000 (LEP 2000) were obtained for the study area. This data was made available by Council in GIS format to facilitate its use in the study.

3.2.3 GEOLOGY AND SOILS

Information with respect to soils and geology was obtained and reviewed for the purpose of this study as described in **Section 2.4**.

3.3 AERIAL PHOTOGRAPHY

3.3.1 HISTORIC

Historic aerial photography of the catchment reviewed in this study included photography taken;

- circa 1948
- August 1963
- December 1974
- May 1993
- June 1995
- April 2001
- April 2003
- June 2004

This data is of variable quality but generally poor compared to current high resolution aerial photography. A copy of an early 1948 photograph of the Yellow Rock Creek junction with Macquarie Rivulet is appended together with a more recent (2004) photograph of the same area.

Figure 3.3.1: Aerial photo of Albion Park- circa 1949 & June 2004

As is apparent on the above photographs, there are few changes in this area over the intervening 55 year period.

3.3.2 PRESENT AERIAL PHOTOGRAPHY

In late 2006 detailed aerial photography of the Macquarie Rivulet catchment was obtained from specialist aerial survey consultants AAM Hatch.. This data, flown in June 2005 is of high resolution (0.2m pixel), giving good definition of surface features. The aerial photo dataset obtained comprises a series of 1500mx1500m photo tiles covering the lower reaches of Macquarie Rivulet as shown below in Figure 3.3.2a together with a high resolution mosaic of the Shellharbour LGA. An extract from one tile in the vicinity of the Eastern Frazer's creek crossing is reproduced in Figure 3.3.2b as an indication of the resolution obtained.

Figure 3.3.2a: 2005 Aerial Photography –Tile Coverage

Figure 3.3.2b: 2005 Aerial Photography – Sample Site
(Frazers Creek Eastern Arm Crossing Tongarra Road)

All aerial photos were orthorectified and geo-referenced to MGA Zone 56 (GDA94) by AAMHatch, to facilitate use with other GIS datasets. This data was used to assist with the development of subareal boundaries, impervious cover for hydrologic models and with the generation of roughness data for use in hydraulic models.

3.4 AERIAL SURVEY (ALS)

3.4.1 METHODOLOGY

For the present study, aerial survey techniques were used as the primary method of collecting topographic data. Specialist aerial survey firm, AAM Hatch were sub-contracted to prepare this data.

The methodology employed is known as Air-borne Laser Scanning (ALS). The ALS equipment is deployed by fixed wing aircraft flying over the site. The ALS equipment emits a continuous stream of laser beam pulses, and records the time taken for each laser pulse to return to the aircraft. This travel time is used to calculate a distance and therefore height of the ground surface relative to the aircraft. Data filtering algorithms are used to remove data that does not represent the true ground surface such as data points collected from roof surfaces or the canopy of a forest.

While this method of survey capture is useful for collection of data over large areas it is limited in that it is unable to collect ground surface data where laser beam pulses cannot penetrate (e.g. from underneath structures such as culverts and bridges or from beneath the water surface). Separate ground survey and bathymetry was therefore obtained to supplement the ALS data in these areas.

3.4.2 DATA COLLECTED

ALS data was collected for the Macquarie Rivulet area where detail 2D hydrodynamic modelling was proposed. The ALS dataset obtained for this study comprised a series of 2000m x 2000m tiles of geo-referenced spot heights. Each tile contained in the order of 500,000 individual spot height data points.

The two datasets of ALS coverage of the Macquarie Rivulet catchment obtained from Hatch are shown shaded outlined in yellow and green in Figure 3.4.2.and at a larger scale in **Appendix B2.** When constructing the 2D model it was found desirable to extend the elevation dataset a little further up the northern side slopes of Marshall Mount Creek. Elevation data in the area was created by merging the LPI contour data with the more accurate ALS data.

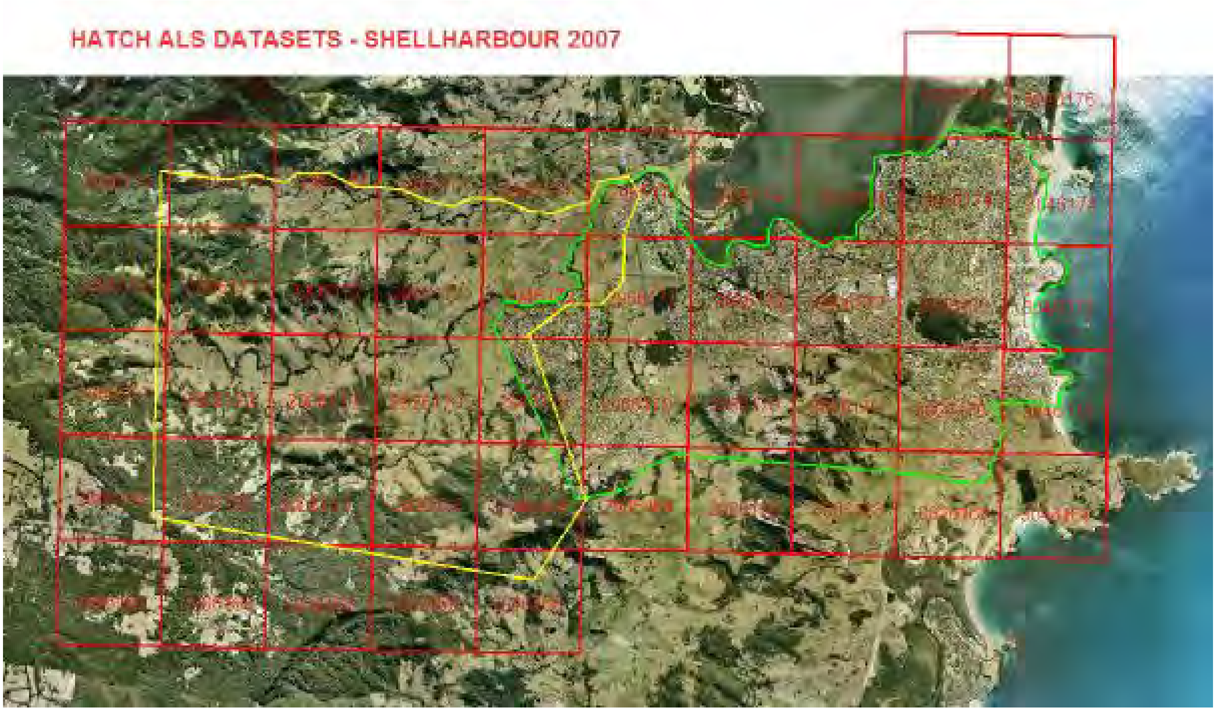


Figure 3.4.2: 2007 Air-borne Laser Scanning (ALS) Tile Coverage

3.4.3 ACCURACY

The filtered data is quoted by the supplier as having an 0.1m vertical accuracy. The spacing of data points varies but typically a spot height has been obtained for every square metre or so of the surveyed surface. This vertical accuracy and dense coverage provides excellent definition of ground features as can be seen from the sample extract of Figure 3.4.3 which shows a small area at the northern end of the main runway, coloured according to elevation. The survey data is of sufficient accuracy that even small drains are well defined and features such as the kerb lines in adjoining streets can be easily identified.

Figure 3.4.3: 20075 Air-borne Laser Scanning (ALS) Example

Ground truthing of the ALS data was carried out at selected locations where ALS and ground survey was available in the same area (typically in the vicinity of structures). It was found that whilst the quoted vertical accuracy of 0.1m was achieved by the ALS in paved or well grazed areas, some over estimation of levels occurred with the bed levels of incised creek channels and in more densely vegetated areas, such as some of the reedy wetlands. Overestimation in the incised creeks was expected and is due to the shadow effect of banks (inhibiting penetration of laser beam pulses), presence of heavy vegetation on the banks and pooled water within the channel invert. In the highly vegetated wetlands, pulses can not reach the underlying ground (at all) with no way of then being able to filter the higher vegetation canopy out using the scatter in elevation returned by adjacent pulses.

The impact of this error on the ultimate conclusions of this study are negligible since the magnitude of flood events investigated in this study (i.e. 1% AEP and PMF) are such that the lower portion of these small creek channels represents a very small percentage of total conveyance. Any underestimation in the depth of these smaller incised channels could therefore only contribute in an entirely insignificant way to uncertainty in flood level estimates in the study area.

3.5 CREEK AND DRAINAGE STRUCTURES (SURVEY)

3.5.1 GENERALLY

In order to supplement the Air-borne Laser Scanning data, separate ground survey of the catchment land surface was required at several locations throughout the catchment. This data was a composite of earlier structure survey provided by David Yates (2007) and more recent structure survey (2009) by Cardno Forbes Rigby

Data was supplied in both electronic form (for direct input to model construction) and hard copy. All data was supplied in a suitably geo-referenced form.

3.5.2 BATHYMETRIC SURVEY

Bathymetric data for Macquarie Rivulet downstream of the weir was extracted from an earlier survey (1990) undertaken by D Allen Surveyor, reproduced from the report by the WRF(1996).

Bathymetric data for Haywards Bay in the general vicinity of the outfall delta of Macquarie Rivulet was obtained from the Lake Illawarra Authority.

This data was merged with the land based ALS dataset to form a contiguous topographic dataset across the area to be modelled.

3.5.3 STRUCTURE SURVEY

A structure survey was undertaken to determine the configuration and dimensions of all significant vehicular, pedestrian and rail crossings in the study area.

An initial review of the catchment was undertaken by RIENCO and each of the structures requiring survey identified. It should be noted that the structures actually incoporated in the hydraulic model were a subset of structures present in the catchment. Only those structures likely to have an impact on flood behaviour in the study area were included.. The locations of all structures investigated are shown in Figure 3.5.3 . Survey data and photographs of each incorporated structure's configuration are provided in **Appendix B4**.

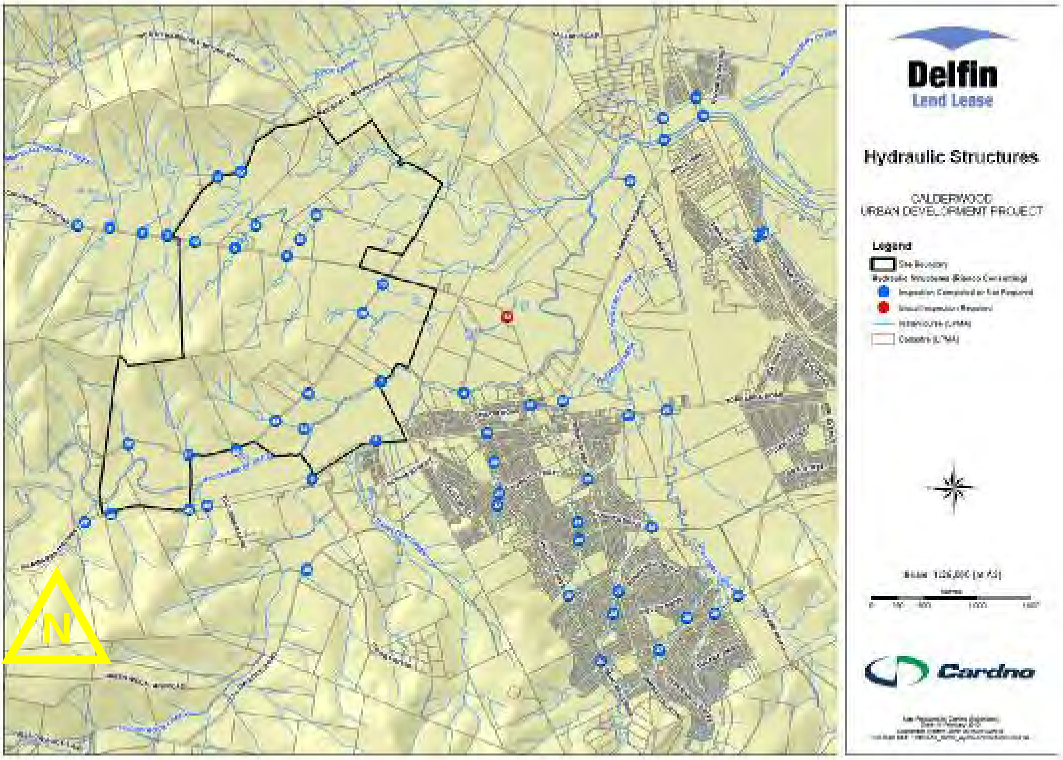


Figure 3.5.3: Structures Reviewed

3.5.4 DRAINAGE INFRASTRUCTURE

A review of drainage infrastructure was undertaken by RIENCO in the latter part of 2006. The objective of this review was to determine the configuration and dimensions of all major trunk drainage lines that might influence flood behaviour within the study area.

This review did not identify any trunk drainage infrastructure that would influence flood behaviour in the study area. It was noted that there is a significant, rapidly expanding drainage network associated with the village of Albion Park, but this would have minimal impact on major flooding in the study area and was not therefore included in this study.

3.6 CREEK AND DRAINAGE STRUCTURES (PHOTOGRAPHY)

A comprehensive photographic survey of the catchment was carried out including photography of each of the creek and drainage structures surveyed. A selection of these photos, relating to the study area in particular, are reproduced in **Appendix B.3**.(Stream Photography) and **Appendix B.4** (Structure Survey & Photography)

3.7 RAINFALL GAUGING

Continuously recording rainfall gauges were installed by the Public Works Department (now Department of Environment Climate Change and Water(NSW)) at Clover Hill (aka Macquarie pass), Calderwood, Upper Calderwood, North Macquarie and Yellow Rock in the mid eighties. These gauges are managed by the Manly Hydraulics Laboratory (MHL) of the Department of Commerce (NSW) for the Department of Environment & Climate Change (NSW). Rainfall gauge locations are as noted in Table 3.7 and shown graphically in Figure 3.7 and at a larger scale in **Appendix A7**

Table 3.7 : Rainfall Gauges in Macquarie Rivulet

Gauge Name	Gauge ID	Easting GDA94/56	Northing GDA94/56	Period of Operation
Calderwood Rd	MHL35	290410	6174300	Jan83-Jun85
Upper Calderwood	MHL36	288600	6174935	Jul85 - present
Nth Macquarie	MHL37	291280	6171330	Jun85 - present
Clover Hill (aka Macquarie pass)	MHL38	284090	6172270	Aug85 - present
Yellow Rock	MHL39	292780	6167430	Jan83 -present
Albion Park Airport	MHL(?)	297190	6173750	Jun91 to Mar95
Albion Pk	SW	295208	6172396	Not Known

Figure 3.7 : Macquarie Rivulet Catchment Gauges

3.8 STREAM GAUGING

3.8.1 GENERALLY

The former Department of Water Resources, now Department of Environment Climate Change and Water (NSW), has recorded flood stage in Macquarie Rivulet near Sunnybank, since August 1949 (S/N 214003). The former Public Works Department, also now Department of Environment Climate Change and Water (NSW), has maintained both a continuous and maximum height recorder near the Princes Highway bridge since 1988 (S/N 214402).

3.8.2 ALBION PARK (AKA SUNNYBANK) GAUGE (S/N 214003)

The Albion Park gauge was installed by the Department of Water Resources in 1949. Over the years, the gauge was relocated several times. In October 1961 the gauge was relocated to a site some 640m upstream of the original gauge site and in March 1978 again relocated a further 500m upstream of the interim site. During the time these various gauges were in service, a number of rating curves were developed to reflect changes in stream geometry and gauging data for each site.

As indicated in Table 3.8.2, no rating data above a discharge of about 10% of the 100 year ARI flow have however been confirmed by measurement at any of these gauge sites.

Table 3.8.2 Albion Park Gauges – Peak Gauging

Site	Flowrate (m3/s)	Gauge Height (m)	Date
3 (1978 to date)	14	1.00	7/11/84
2 (1961-1978)*	64*	1.79*	21/6/75*
2 (1961-1978)	7	1.05	19/10/76
1 (1949-1961)	11	1.1	22/10/59

Source: WRF report on Macquarie Rivulet as a Reference Catchment (1986)

**1975 estimate only based on surface floats (DWR records)*

The NSW Department of Water Resources extrapolated the rating curve to higher flows based upon the creek cross section at the gauge and average stream bed grade. It is likely, however, that the section has since altered as a result of scour and the DWR rating curve should be considered approximate only. In a study undertaken for the Water Research Foundation (WRF (1996)), this concern was reinforced when difficulties were experienced by several committee members while trying to calibrate models to discharges predicted by the DWR rating curve. To explore the problem further, cross sections of the stream were surveyed and a static 1D hydraulic model (HEC2) used to simulate the stage/discharge relationship at this gauge. Both the current DWR and WRF rating curves for the Sunny Bank site are reproduced in Figure 2.12.2 and at a larger scale in **Appendix B8**. As will be apparent from the two plots, the original DWR curves predicts much greater discharges for any stage than does the HEC2 based curve.

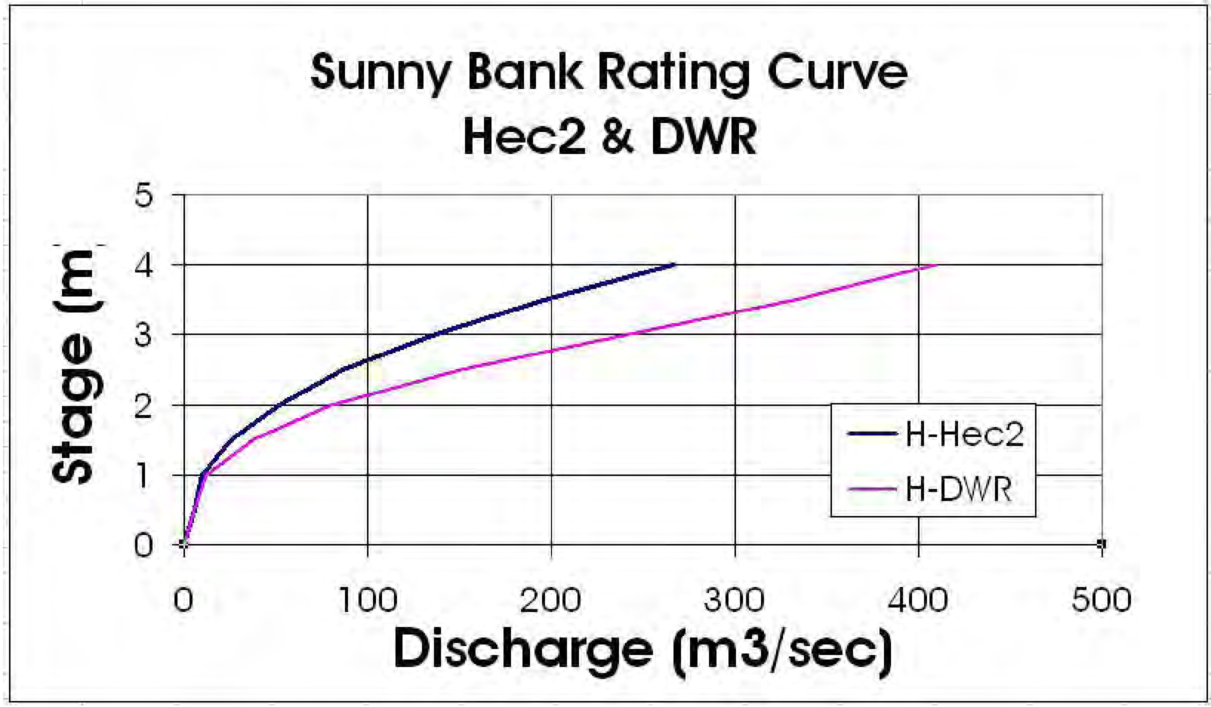


Figure 3.8.2 : Albion Park CSR Rating Curves

Photographs of the stream in the vicinity of the present gauge are reproduced in **Appendix B3** . The present gauge location is shown graphically on an aerial photographic underlay in **Appendix A7.**

3.8.3 PRINCES HIGHWAY GAUGE (S/N 214402)

The former NSW Public Works Department, now Department of Environment Climate Change and Water (NSW), installed a Maximum Height Indicator (MHI) and a continuous flood stage recorder (CSR) on Macquarie Rivulet at the Princes Highway in 1988. These gauges are located on the south bank of Macquarie Rivulet, a short distance downstream of the Princes Highway road bridge

No formal rating curve has been developed for the continuos stage recorder. In a study by the Author for the Water Research Foundation (1996) a provisional rating curve was however developed based upon a static, two dimensional hydraulic model of Macquarie Rivulet. This rating curve is reproduced in Figure 2.12.3, together with a larger scale version in **Appendix B9**.

Above RL 2.0m AHD Lake levels have little impact on levels at the gauge. Below RL 2.0m AHD, the rating curves become progressively impacted by the elevation of the lake into which the rivulet discharges, requiring a family of rating curves to relate stage to discharge for each lake tailwater level. It should be noted that modelling for this rating curve has not considered the impact of lake levels above RL 3.00m AHD or the hysteresis present in a real event when discharges on the rising limb differ from that on the falling limb for a particular flood stage at the gauge. Provided Lake levels do not exceed RL 3.0m AHD, this rating curve should however provide a reasonable correlation between stage and discharge.

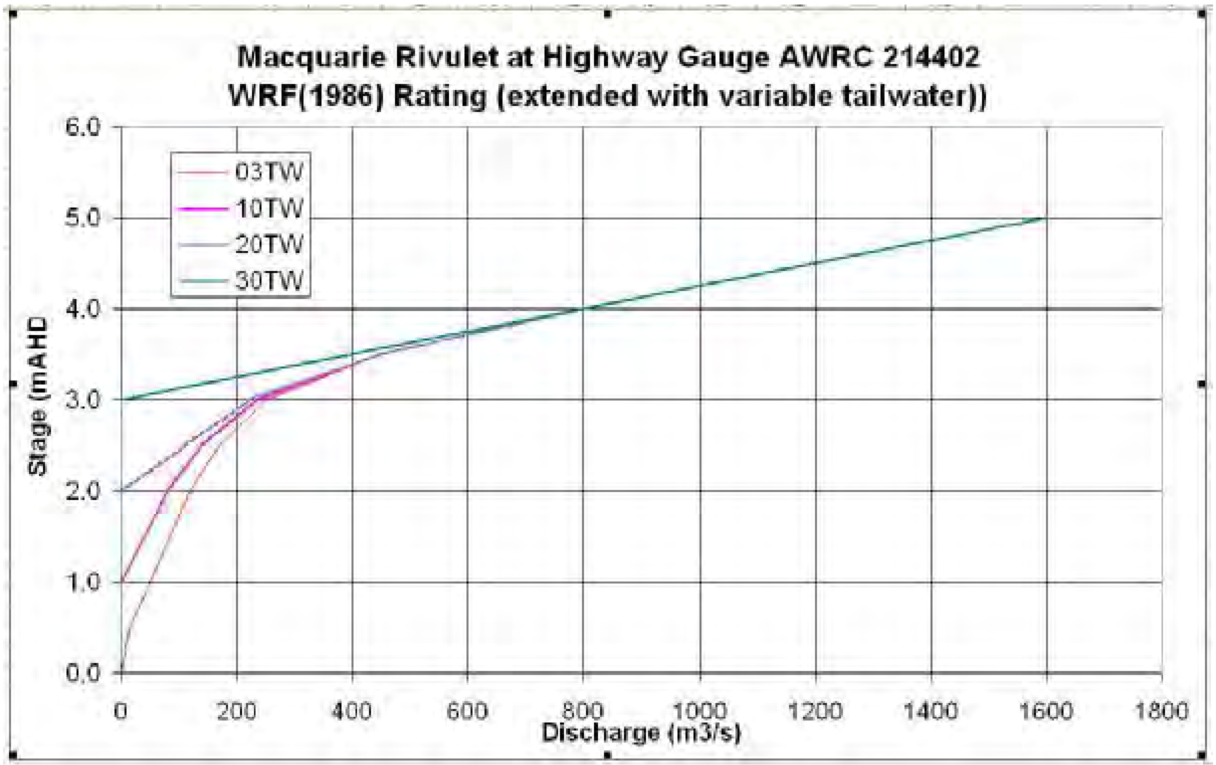


Figure 2.12.3 : Princes Highway Provisional CSR Rating Curve

Photographs of the stream in the vicinity of the present gauge are reproduced in **Appendix B3** and the gauge locations shown graphically on an aerial photographic underlay in **Appendix A7**.

3.9 HISTORIC RAINFALL AND FLOODING

3.9.1 HISTORIC RAINFALL

Historic rainfall data was sourced from rainfall gauges administered by Manly Hydraulics Lab (MHL). Some data for the June 1991 flood event was also obtained directly by RIENCO from gauges administered by Sydney Water and the NSW Rural Fire Service. Since meaningful rainfall data is only available for the events occurring after rainfall gauges were installed in the catchment in the early eighties, this review was restricted to storms occurring from February 1984 up to the present time, as listed in Table 3.9.1 below.

Table 3.9.1: Rainfall Data Reviewed for Current Study

Event	Description	Rainfall (Daily)	Gauge Data Reviewed
February	This was an extremely severe	850mm	Two MHL rainfall gauges were

1984	event, centered on West Dapto causing extreme flooding in Mullet Creek. A steep rainfall gradient away from the Mullet Creek catchment created only moderate to minor flooding in adjoining catchments.		present in the catchment at this time however only one (Calderwood) was operable.
August 1986	253mm in four days. Albion Park rail under water up to 0.5m but Shellharbour suffered little damage	110mm	Limited Data - Not Pursued
August 1987	Major flooding in northern suburbs of Wollongong but only minor flooding in Shellharbour	160mm	Limited Data - Not Pursued
April 1988	Moderate flooding throughout Shellharbour Wollongong but Shellharbour not as impacted as northern suburbs.		Limited Data - Not Pursued
June 1991	This was a severe event of the order of 10-50 year ARI centered on catchments around Lake Illawarra. It was a relatively long duration event and therefore did not cause major flooding in smaller catchments but did create significant flood discharges in larger catchments (such as Macquarie Rivulet) and did elevate lake Illawarra significantly (RL 1.9m AHD)	310mm (800-1000 mm over 5 days)	Data was available from six MHL rainfall gauges located within or near to the catchment and a Sydney Water gauge within the catchment. All were operable.
August 1998	This was a very severe event in the northern suburbs of Wollongong with relatively little rain falling south of the Wollongong CBD.	316mm	Six MHL rainfall gauges were located within or near to the catchment. Only three were however operable.

In reviewing available rainfall data, all data was first checked for missing and/or unreasonable data and any clearly erroneous datasets discarded from further consideration. The data was then assessed for its suitability for model calibration. Suitability for model calibration was based on:

- The data being from a location within or close to the catchment and therefore representative of rain falling on the catchment
- The data being of high quality (no missing rainfall values)(sensible volumes)
- The data extending for the full duration of storm
- The event being of sufficient severity as to generate flooding of some consequence
- Corresponding historic flood level information being available for modelled reaches (either from continuous stage recorders (CSRs), Maximum Height Indicators (MHIs) or surveyed flood debris).

Whilst all of the above storms were reviewed, only the June 1991 data was identified as suitable for model calibration and subsequently processed into a format suitable for modelling. Whilst the June 1991 event did not generate particularly severe flooding, it did involve significant overbank flooding and was the only event for which substantial reliable historic rainfall and flood level information was available.

The June 1991 rainfall hyetographs for each gauge, used in modelling the calibration event, are reproduced in **Appendix B5**.

As is apparent in these plots, the June 1991 event was of long duration (5days) with several peaks in rainfall intensity during that time. The two most intense rainfall peaks occurred on the first and last days of the storm event. For a 9 hour or so duration ('critical' duration for the catchment as a whole), the storm corresponds to about a 5 to 10 year ARI rainfall event.

Further discussion on rainfall data is provided in **Section 6**.

3.9.2 HISTORIC FLOODING

Historically, the village of Albion Park has been subject to flooding on several occasions in the past. This recurrent flooding was the trigger for the flood study prepared by the Water Resources Commission in the early eighties.

The low section of the Illawarra Highway between the Princes Highway and Tongarra Road floods every few years, as does Tongarra Road in the vicinity of the West Frazer's Creek crossing. Construction of a new (higher) Princes Highway bridge has eliminated the flooding that also took place at this crossing every few years. Mansons Bridge (Calderwood Rd) also has been observed to overtop in major events. Local storm drainage system inadequacies have been a recurrent source of flooding in the village of Albion park.

While not directly part of the Macquarie Rivulet catchment, the Princes Highway in the vicinity of the Albion Creek crossing, also floods every few years.

Information on historic flooding prior to the February 1884 event has been collected from various sources and is reproduced in the following.

Event of March 1983

- 5 hours of torrential rain on 22 March 1983 following three days of continuous rain.
- Flooding at Fairy Meadow
- Flooding of many houses in northern and southern suburbs. In Shellharbour reports of flooded houses.

Source - Little Lake Flood Study Compendium of Data

Event of October 1983

- Constant rain throughout night of 13th and morning of 14th October 1983 caused flooding in southern Wollongong suburbs.

- Albion Park township flooded. Airport under 0.5 m water. Roads into Albion Park were cut off.

Source - Illawarra Mercury 15/10/83

Event of April 1978

- Moderate flooding in some suburbs.
- Mr Trevor Batson of Hillside Drive had flood waters in all the rooms of his new home.

Source - Public Works Brief for Macquarie Rivulet Flood Plain Management Study.

3.1.9 Event of March 1975

- Heavy thunderstorms occurred over the Illawarra and Sydney Metropolitan areas between Sunday 9 March and Tuesday 11 March 1975.
- For the 24 hours ending 9am, 11 March 1975, rainfall depths of up to 300 mm were recorded in the eastern portion of the Macquarie Rivulet catchment.

(Source - Bureau of Meteorology, 1976)

Other Events

(Source :Public Works Brief for Macquarie Rivulet Flood Plain Management Study)

Event of May 1969

- Mrs J. McGregor of Station Street had flood waters to the porch of her house. It was blamed on the inadequacy of the three storm water pipes under Station Street.

Event of December 1960

- Terry Street was closed by flood waters up to 4 feet deep and stretching for 200 yards.

Event of October 1959

- Many homes in Station Street had floor coverings ruined by flood waters.

Event of February 1959

- Flood waters were reported to be 2 feet deep on the bitumen approach to Macquarie Rivulet bridge.

Event of March 1959

- Terry Street was completely submerged by 3 - 4' of water between Albion Park and Meadow View Farm.

Event of May 1950

- The highway at Albion Park was closed for a distance of half a mile by flood waters which were up to 6 feet deep.
- The flood waters lapped into the Commercial Hotel and newspaper shop and there was 18 inches of water across the intersection of Flinders and Terry Streets.

Event of June 1949

- Flood waters reached the corner of Terry and Flinders Streets and the posts along the road north of Albion Park were not visible.

Event of May 1941

- Flood waters were 6 inches high in O'Gorman and Sons Butchery.

Resident Interviews

Mr King

Local resident, Mr King recalled that in 1950 the flood waters reached the verandah of the Commercial Hotel. Mr O'Gorman's butcher shop had to have the front and back doors sand bagged to prevent the entry of flood waters. The Commercial Hotel at this time was located on the N.W. side of the intersection of Terry and Flinders Streets. The original hotel was burnt down in 1954 and rebuilt on the adjacent corner where it is now. The 1950 flood also caused 18" of water across the intersection of Terry and Flinders Streets. According to Mr King, the floods have never reached such a height since Council's drainage works on the northern side of the Town.

Minor flooding also occurs in Calderwood Road and flood waters have been up to 2 feet over the deck of Manson's Bridge, but the water has never entered the homes in the bridge's vicinity.

Shell Garage, Tongara Road

Mr Harris has lived in Albion Park for sixty odd years and recalls the following details :

1. In 1978, flood waters were one foot over Manson's Bridge, Calderwood Road.
2. Flood waters have on several occasions reached the fence around the police station.
3. Flood waters have regularly entered the General Store and O'Gorman's Butcher Shop.
4. The cricket oval is regularly flooded and water has reached up to the concrete path behind where the new supermarket has opened at the show ground entrance.
5. Flood waters have reached the steps of the new 'Commercial Hotel'
6. The houses at the end of Hamilton Street have been flooded

.

7. Flood waters have been lessened since the Council removed the wooden bridge near Boles Farm in1965. The council put in concrete bank protection and raised the road and river to prevent the river from breaking its banks and flowing into the swamp on the southern side of the road. This may have temporarily relieved the flooding caused by the Rivulet combining with the flood waters from Frazers Creek and flooding the Albion Park township. The swamp area south of Boles Farm acted as a retention basin but now the flood waters are forced north westward causing increased flooding on farms on the other side of the river. Eventually the Rivulet and Frazers Creek flood waters pool back to swamps.

8, In Croome Street, Greenmeadows, is subject to flooding. Flood waters have entered houses on two occasions since the opening of the Estate, and residents have had to remove fence palings to allow the flood waters .to pass

9. Frazers Creek regularly floods, closing the road but the waters drop as quickly as they rose.

Mr Russell, Meadow View Farm, Illawarra Highway

Felt that the 1978 flood was the worst flood he had experienced since the 1960's. Flood waters reached between the two Railings of the front gate and the waters reached within 15 feet of his front door as well as reaching the cement slab in front of the dairy.

3.10 PREVIOUS STUDIES

The catchment of Macquarie Rivulet has been the subject of several flood related studies completed over the last quarter of a century. Those published prior to 1996 were reviewed and summarised in the report by the Water Research Foundation Illawarra Committee (refer Water Research Foundation (1996)). All studies reviewed in the course of this study are listed below, but those previously reviewed in the WRF(1996) report have not been further discussed in this report.

WATER RESOURCES COMMISION NSW

- *Albion Park Flood Study Report (1986)*

WARGON CHAPMAN & ASSOCIATES

- *Report on Investigation for New Railway Bridge Over Macquarie Rivulet at Albion Park 101.169 km (Illawarra Line) (1980)*

FORBES RIGBY PTY LTD

- *A Report on the Impact of Flooding on the Development of Land at Macquarie Rivulet, Yallah (1990*
- *A Supplementary Report on the Impact of Development of Land Adjacent to Macquarie Rivulet on Flooding in Macquarie Rivulet (1991)*
- *A Review of Flooding in the Lower Reaches of Macquarie Rivulet and the Potential for Cross Flows from Macquarie Rivulet into Albion Creek (1993)*
- *A Review of Flooding in the Lower Reaches of Macquarie Rivulet and the Impact of Development on Flooding (1994)*

- *A Review of Flooding at the Corner of Terry St and Tongarra Rd Albion Park, NSW (1995).*

KINHILL ENGINEERS PTY LTD

- *Extension to Albion Park Flood Study (1993)*

The studies completed post publication of the 1996 WRF report, together with the WRF report itself, are summarised as follows.

WATER RESEARCH FOUNDATION

A Report on Development of Macquarie Rivulet as a Reference Catchment for the Illawarra(1996)

This report, edited by Mr Rigby, was prepared for the Water Research Foundation by the Illawarra Regional Committee of the Water Research Foundation. This committee was set up after major flooding in Mullet Creek in February 1984, to share information on flooding in the region generally and to collate and analyse data for rainfall and flooding in Macquarie Rivulet, with a view to establishing Macquarie Rivulet as Reference Catchment for flood modellers practicing in the region.

This report and the report's companion 'Compendium of Data' are a highly useful source of information on the catchment and historic flooding within the catchment. The report in addition provides insight into appropriate hydrologic model calibration in the catchment and questions the voracity of the current rating curve for the Albion park (Sunnybank) continuous stage recorder. An alternate rating curve based on hydraulic modelling is proposed and a provisional rating curve was developed for the continuous stage recorder below the Princes Highway Bridge. Using these amended rating curves, a group of committee members were able to independently obtain good correlation between the discharges predicted by their various models and discharges recorded at the two gauges, lending weight to the reasonableness of the rating curves and calibrations adopted. Of particular value to the present study is the comprehensive dataset, collected at the time, on flooding in the June 1991 event.

LAWSON & TRELOAR

Lake Illawarra Flood Study (2001)

This study was undertaken for the Lake Illawarra Authority, Wollongong City Council and Shellharbour City Council. The study is confined to consideration of lake flood behaviour and does not address the behaviour of streams feeding into the Lake. With respect to Macquarie Rivulet, the study identifies limits of flooding due to elevated water levels in the lake for a range of events including the 1% AEP and PMF events. This flood behaviour, including a table documenting flood levels in the Lake near the Macquarie Rivulet mouth, is described in **Section 7**.

The study determined that the critical storm duration for the lake is 36 hours (using the standard Australian Rainfall & Runoff design flood estimation procedure). It was also found that flooding in the lake is controlled largely by the hydraulic constriction at the lake entrance near Windang, accordingly there is negligible spatial variation in lake flood level across the outlet of Macquarie Rivulet. The resulting peak 1% AEP lake flood level near the outlet of Macquarie Rivulet is reported as being 2.30 mAHD whilst the corresponding PMF flood level is 3.24 mAHD. Stage hydrographs are provided for the 1% and PMF design events.

Lake Illawarra Floodplain Management Study & Plan (2005)

This study was prepared for the Lake Illawarra Authority, Wollongong City Council and Shellharbour City Council to formulate and assess management options for reducing the impact of flooding in the vicinity of the lake. Hydraulic hazard was reassessed during this study and a Floodplain Management Plan prepared.

Riverine flooding due to flow in Macquarie Rivulet was outside the scope of this study, however options for dealing with flood problems due to lake flooding are considered. Flood levels derived from the Lake Illawarra Flood Study (Lawson & Treloar, 2001) are therefore of relevance to the current study and were incorporated as described in **Section 7**.

RIENCO CONSULTING

Flood Modelling Report – Land Adjacent to Albion Park Airport (Existing Conditions) (2007)

This study of the combined Macquarie Rivulet/Albion Creek catchments was commissioned to quantify existing flood behaviour in Macquarie Rivulet adjacent to the southern end of the Albion Park Airport runway as a base for consideration of flooding impacts associated with a proposed light industrial development between the southern end of the runway and floodplain of Macquarie Rivulet. Albion Creek was included as earlier modelling had identified a diversion flow path over the north south runway from Macquarie Rivulet into Albion Creek at about the level of a 1% AEP flood in Macquarie Rivulet. This study utilised wbnm as its hydrology model and tuflow as its 2D hydrodynamic model to simulate food behaviour. The models were independently calibrated to an event occurring in June 1991. This study confirmed the findings of earlier modelling with a near level pool of floodwater developing on the Macquarie Rivulet floodplain to the west of the airport at about RL 6.5mAHD in a1% event and RL 8.5mAHD in a PMF event. In a PMF event, massive quantities of flow (relative to Albion Creeks local flow rate) overtops the runway to inundate at depth most development in Albion Creek's catchment, between the runway and the Lake

Flood Modelling Report – Land Adjacent to Albion Park Airport (Post Development Conditions) (2007)

This study built upon the 'existing' conditions model, adding a modified topography together with buildings/roads as proposed, to quantify the impact such a proposal might have on flood behaviour in the vicinity of the proposed development. Modelling confirmed that in general the proposed development would raise flood levels on the floodplain to the west of the site by about 50mm in a 1% AEP event and 25mm in a PMF event.

Flood Modelling Report – Hyundi Dealership, Princes H'way, Albion Park Rail (2007)

This study refined the earlier airport modelling, adding solid building outlines and paved yards with fences in the light industrial area to the south of Macquarie Rivulet, between the road and rail bridges and south along the Princes Highway. The upgraded model was then run to re-establish the 'existing' flood surface and the proposed development layout added as a further variation to quantify the impact of the proposed development on flooding in the vicinity of the site. Some small elevation of flood levels in a 1% post-development event was noted but the depth of flooding in a PMF event was unaltered. In both a 1% and PMF event, the study indicates that floodwater backs up at the rail line until it overtops the line, creating a relatively flat peak flood surface from the rail line back up to the highway. As previously noted, flow in Albion Creek (and flood depth and velocity) increases rapidly once the runway overtops creating a quite dangerous environment for those occupying the floodplain of Albion Creek in such an event. The study established a peak flood surface level at the site in a 1% AEP event of RL 3.0mAHD and a PMF level of 5.8mAHD.

4 HYDROLOGIC MODEL ESTABLISHMENT

4.1 MODEL SELECTION

The Macquarie Rivulet catchment is a catchment of moderate complexity with some significant areas of substantial flood plain storage. There are several structures (bridges, culverts and basins) on streams within the catchment and diversions of flow can develop at several locations between sub-catchments. Accordingly, the hydrology model proposed must be able to simulate these real world complexities.

The hydrologic computer model selected for use in this study was the WBNM (Watershed Bounded Network Model) developed by Boyd, Rigby, and Van Drie. WBNM is a lumped parameter (runoff-routing) model that has been developed locally and used extensively in the Illawarra region. Detailed information with respect to the model can be obtained from the website http://www.rienco.com.au/index.php?v=Research_and_Development

Successful calibration has been achieved using WBNM on many catchments similar to the study catchment. A high degree of confidence can therefore be ascribed to the models predictions. One of the model's particular strengths is its ability to model complex arrangements of storages and diversions, as exist in this catchment.

4.2 MODEL CONSTRUCTION

4.2.1 SUBAREA TOPOLOGY

WBNM model construction requires the overall catchment to be broken down into a number of sub-areas, each sub-area representing a discrete watershed region. Sub-areas were delineated using computer based GIS software in combination with the ALS ground surface data.

Initially the overall catchment was broken down into broad sub-catchments corresponding to the main arms of Macquarie Rivulet (as shown in **Appendix A.6**). Each of these arms was then further broken down into component sub-areas according to natural patterns of internal tributaries and the location of structures such as culverts, bridges, abnormal areas of floodplain storage and diversions. A Subareal plan of the model is reproduced in Figure 4.2.1. In this figure, the clear subareal polygons are subareas that will be used to obtain 'local' flows for input to the hydraulic model. The blue shaded subareas are subareas that will be used to obtain 'total' inflows to the hydraulic model and while very much part of the hydrologic model, the green shaded areas are not directly used in the hydraulic model at all. The full catchment layout and an annotated enlargement of the layout in the vicinity of the site are provided in **Appendix C1.**

.

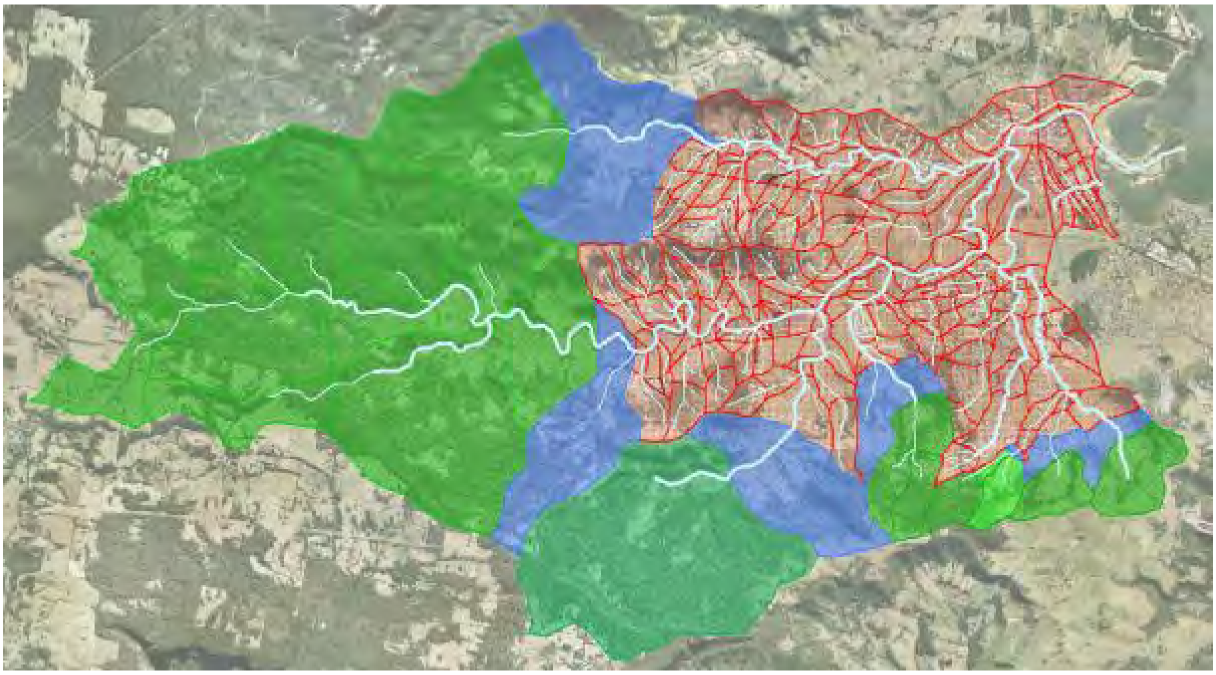


Figure 4.2.1` : WBNM Model Topology

In the final hydrologic model, the catchment was broken down into a total of 232 sub-areas. In order to facilitate ready location of these sub-areas, a node based naming convention was developed based on the Arm ID and an alphabetic character string. YellE(1)A for example describes a subarea at the head 'A' of the first branch '(1)' off the fourth subarea 'E' on the Yellowrock arm. Any subarea ending in an 'A' is a head subarea. More detailed layouts of sub-catchments with these identification labels are reproduced in **Appendix C.1**

Once naming was completed, the physical properties of each sub-area were calculated using MAPINFO. The area in hectares, co-ordinates of the outlet and co-ordinates of the sub-area centroid were each calculated in an automated manner using GIS techniques in a form suitable for direct input to WBNM.

4.2.2 CALCULATION OF IMPERVIOUS COVER

Impervious cover (i.e. the proportion of impermeable surfaces such as rooves, roads, bitumen and concrete in each sub-area), is a key physical parameter affecting both the quantum and timing of runoff from a catchment. Traditionally these values are estimated from zoning maps using typical percent impervious cover levels for each zone. While such an approach is quite straightforward once each zone is fully developed, mapping to a model subarea becomes difficult when zones are not fully developed, typically requiring further separation of the developed and undeveloped areas of each zone

In this study, GIS techniques were used to directly associate percent impervious cover with areas of different (hydrologic) land use identified on the aerial photographs and to allocate impervious cover to each model subarea. This involved a three step process as described below.

Step 1
This initial step involved the development of a base (hydrologic) landuse map from the high resolution aerial photography flown in 2005.

- In this step a hydrologic landuse plan was created identifying the spatial extents of each of the different hydrologic landuse classes and updated to reflect new development between 2005 and 2009. This is reproduced in Figure 4.2.

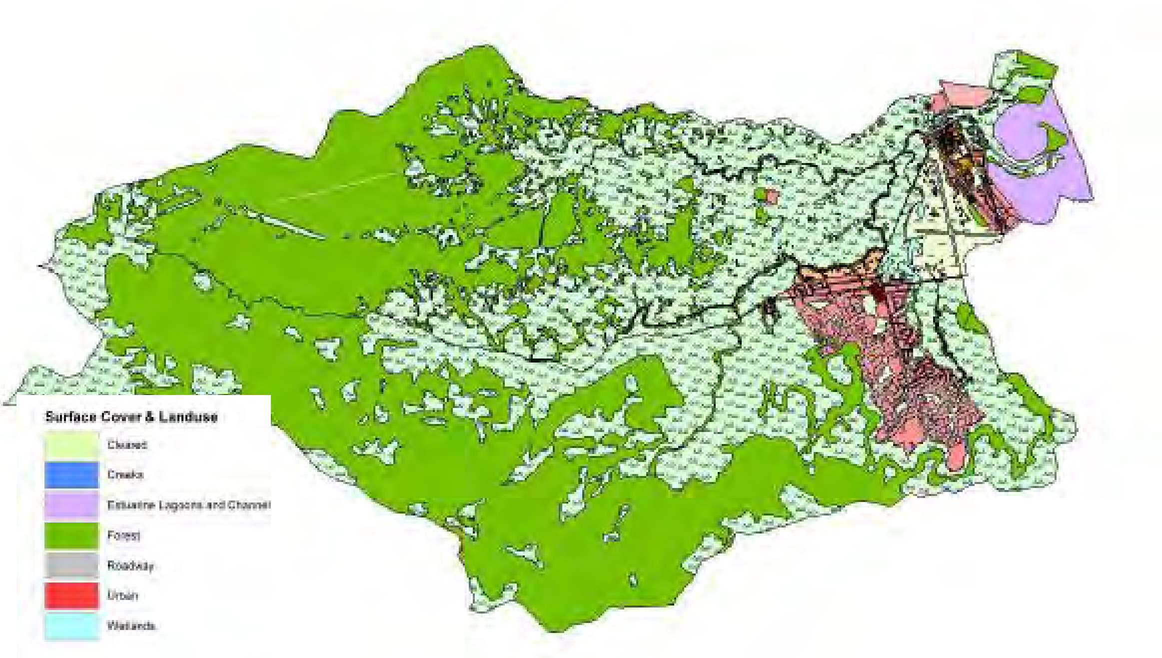


Figure 4.2.2a : Hydrologic Land Use Classes (2009)

Step 2
The next step involved the estimation of impervious cover values for each hydrologic landuse class.

- As a quite detailed review of impervious cover levels in the adjacent Horsley catchment had been recently completed involving both manual site sampling and several spectral analysis techniques, the values derived from this work were adopted in this study. These values are set out in Table 4.2.2 for each of the above classes. As commercial and industrial land uses were relatively limited in extent and vary across a wide range of impervious cover levels, they were lumped with residential land uses under a single 'urban' landuse.

Table 4.2.2: Adopted Impervious Cover Levels

Landuse Class	%Imp
Cleared grassland	0
Creeks (Ephemeral)	0
Estuarine lagoons/channels	100
Forested Areas	0
Roadway & paved areas	75
Urbanised areas	51
Wetlands (Ephemeral)	0

Step 3
This last step involved the use of GIS to allocate impervious covers to each subarea and to provide tabular input of subareal geometry and impervious cover to the hydrologic model WBNM.:

- In this step GIS software (MAPINFO) was first used to associate each land use with a particular attribute of impervious cover, as calculated/estimated in Step 2 above. The hydrologic model subarea's (as shown in **Appendix C.1**) were then overlaid and the impervious cover from each of the hydrologic landuses (contained within each subarea) used to calculate each subarea's overall impervious cover (from each component landuse). Tables were configured in the process to provide direct input of this information to WBNM.

The above methodology takes advantage of the excellent resolution of the aerial photography to reliably estimate different land uses and impervious cover for the catchment and removes any subjectivity from the estimation of the proportion of landuse within each subarea. A thematic map of the catchment is presented in .Figure 4.2.2b showing the calculated impervious cover levels for each subarea. The concentration of impervious cover in the eastern half of the catchment, around the Princes Highway and village of Albion Park, Is readily evident in this plot.

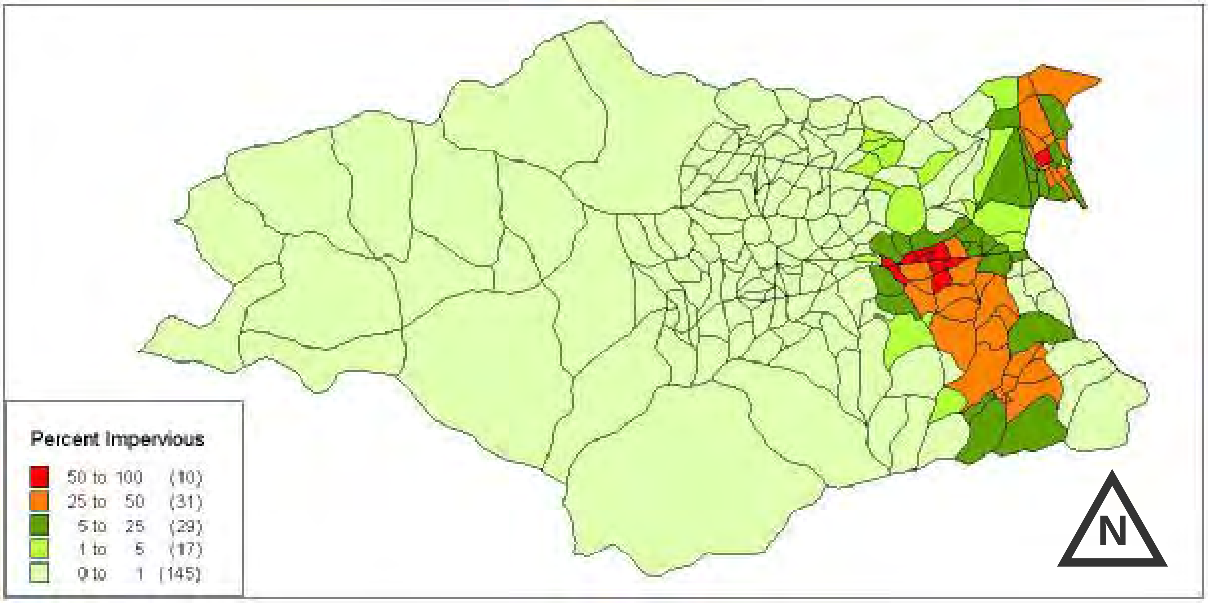


Figure 4.2.2b: Impervious Cover in Each Sub-Area (2005)

4.2.3 BASINS

There are a number of small basins (retarding basins or ponds) in the Macquarie Rivulet catchment. Most are associated with recent development around the village of Albion Park, aimed at maintaining post development peak discharges to pre-development levels. As this study focuses on flooding in the mainstream of Macquarie Rivulet and Marshall Mount Creeks, these small local basins have not been incorporated into present hydrologic modelling.

4.2.4 AREAS OF (ABNORMALLY) HIGH FLOODPLAIN STORAGE

Most floodplains exhibit 'normal' storage characteristics and can be adequately described by implicit computation of their storage/discharge characteristics based on the overall catchment lag coefficient C. Occasionally areas of 'abnormally' high flood plain storage are encountered. These areas are normally visually obvious during a flood being typically much more extensive and deeper than floodwater built up elsewhere on the floodplain. If in doubt, the implicit storage associated with a given discharge can be compared with that determined explicitly (typically by hydraulic modelling). If there are significant differences, the hydrologic model should be built with explicit storages in the area of 'abnormal' storage.

Several sub-catchments were identified in the catchment of Macquarie Rivulet as containing abnormal' floodplain storages. These areas are shown in Figure 4.2.5 and at a larger scale in **Appendix C3.**

Since flow passing through these sub-areas is explicitly routed through their associated storages, no routing as provided implicitly by catchment lag is necessary. In sub areas with abnormally high flood storage, C is set to zero if the flood storage would cover most of the sub-area, eliminating both local overland and stream attenuation arising from implicit storage-lag. Where the abnormally high flood storage only covers a small part of a much larger sub-area, C is left at its default value and the watercourse factor reduced to zero. In this way only the implicit stream routing is eliminated.

4.2.5 DIVERSIONS

Potential for diversion of flow between various subareas was identified based on a combination of field inspection, detailed review of ALS/Aerial Photography, engineering judgement and feedback from preliminary hydraulic model runs. These potential diversion paths have been shown on the Hydrologic Model Diversions plan included in Figure 4.2.5 and at a larger scale in **Appendix C.3**.

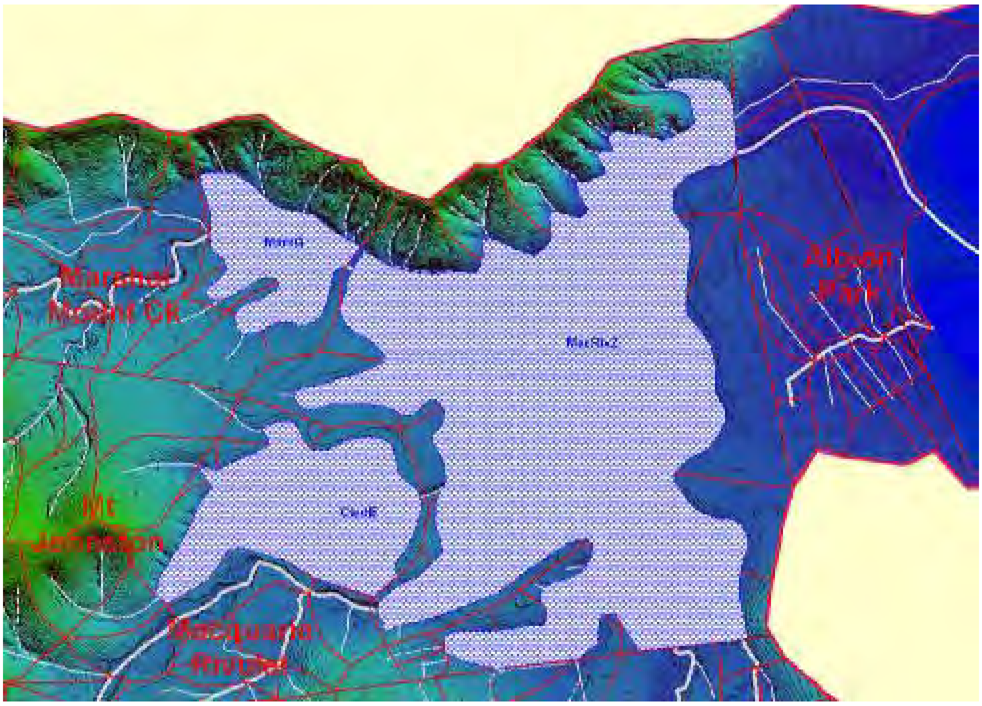


Figure 4.2.5: Areas of Abnormal Floodplain Storage and Diversions

The discharge characteristics of each diversion (variations in discharge to each downstream point with flood stage) were calculated using a combination of hand hydraulic calculations and hydraulic modelling. This resulted in stage/discharge relationships (rating curves) for each diversion that could be input to the hydrologic model's structure routines.

4.2.6 DESIGN RAINFALL

Three 'design' rainfall gauges were constructed for the catchment with names and locations as listed in Table 4.2.6. The locations of the three gauges were selected to describe the spatial distribution of rainfall across the catchment including, in particular, the significant east-west rainfall gradient. IFD characteristics for each gauge were derived using standard procedures as described in AR&R 1987.

Table 4.2.6 Location and description of design rainfall gauges

Design Gauge	Gauge Location (E,N)	Description of Location
Macriv #1	290046.30 6172300.00	On Macquarie Rivulet, in center of catchment
Macriv #2	285724.60 6172576.80	On Macquarie Pass, in catchment headwaters
Macriv #3	295050.00 6172240.00	In Albion Park Village, in lower catchment

The locations of these three 'design' gauges are shown in red on the Catchment Gauges plan reproduced in **Appendix A.7**.

4.2.7 ESTABLISHMENT OF HYDROLOGIC PARAMETERS

Hydrologic parameters required for input into the WBNM model runfile are described in Table 4.2.7 below along with a description and explanation for the values adopted. It is noted that some of these values were subsequently amended during calibration (refer **Section 6**).

Table 4.2.7 Hydrologic Model Parameters

Hydrologic Parameter	Description	Value Adopted
Catchment Lag 'C'	This parameter governs the lag time taken for rainfall to be converted to runoff for the natural (pervious) portion of a particular subarea. A quick response natural subarea has a short lag time whilst a slow response natural subarea has a long lag time. Extensive research carried out at the University of Wollongong (Boyd *et al*) has found that the value of C used to calculate the lag time is insensitive to most natural catchment characteristics. other than area (refer WBNM user documentation for further description).	The value adopted by this study for Catchment Lag 'C' is 1.3. It is noted that the current WBNM user guide recommends a general value be applied in the vicinity of 1.6 based on analysis of historic flow gauge data (generally this data was sourced from catchments external to the Illawarra). However, when coupled with stream roughness values applicable to streams in the Illawarra, better overall calibration has been previously achieved by the authors using the lower value of 1.3. This value has therefore been adopted in the initial hydrologic establishment phase.

Impervious Lag	The Impervious Lag factor is derived from the value of C (described above) and applied to impervious portion of a catchment. It represents a percentage of C (i.e. an Impervious Lag factor 0.1 means that impervious surface lag is only 10% of that from a natural pervious surface catchment). This accounts for the much faster response time from the unnatural (impervious) portion of a particular subarea.	The recommended value of 0.1 was adopted for this study. This value has been used in previous Illawarra studies for which successful calibration has been achieved and is recommended by the authors of WBNM.
Stream Lag	The stream lag is also derived from the value of Catchment Lag 'C' and is used for non-linear routing of flow through subareas containing a natural watercourse. The value of Stream Lag reduces with increasing velocity as would result from channel straightening and lining. The user guide recommends a value of 1.0 for natural streams, 0.5 for earth lined channels, and 0.33 for concrete lined channels.	The recommended values have been adopted for the current study. A value of 1.0 was applied to the majority of catchments as most have natural or semi natural features. Time delay of 0.5 minutes (i.e. no stream routing) was used on all dummy nodes and those subareas with a very small area (say 0.1ha).
Initial Storage levels	WBNM permits storages to be modelled with a starting water level other than completely dry (i.e. part full). This may be relevant where storages have a slow drawdown rate and/o where antecedent rainfall has partially filled the basins.	All storages were assumed dry at the commencement of modelling, reflecting the conditions known to prevail in the calibration model and as would likely apply prior to a long duration 36 hour design storm.

Losses Initial Loss (IL)	Initial losses represent the amount of rainfall lost to groundwater at the beginning of the storm. They closely reflect the 'dryness' of the catchment prior to the storm being modelled and soil characteristics (permeability and storage potential in particular). (shallow highly impermeable clays have a low IL while deep loamy or sandy soils have a high IL).	For model establishment and calibration an Initial Loss of 15mm was initially proposed reflecting a typical NSW catchment with limited lead up rainfall as per measurements by Cordery Web *(1974) (This was later increased to 150mm for the calibration event to better match the early stage of the recorded hydrographs at Sunnybank and the Princes Highway.)*
Continuing Loss Rate (CLR)	Continuing losses represent the amount of rainfall lost to groundwater during the storm after abstraction of initial losses. They closely reflect the soil types within a catchment (shallow highly impermeable clays have a low CLR while deep loamy or sandy soils have a high CLR).	A Continuing Loss Rate of 2.5mm per hour was used in modelling both the calibration and design events, reflecting typical values used in the Illawarra. It is noted that the predominantly clay based soils in the catchment have low permeability therefore a CLR of the order of 2.5mm/hour is considered appropriate.

4.2.8 PRELIMINARY MODEL CHECKS

The WBNM model runfile was initially constructed using the catchment data and parameters described in the previous sections. Prior to model calibration (refer **Section 6**), the following preliminary model checks were undertaken using a 9 hour, 1% AEP design rainfall burst:

Overall volume conservation:
The total runoff volume (as calculated at the catchment outlet) was checked against total rainfall volume (i.e total amount of rain falling on the entire catchment surface). As expected from a correctly constructed model, these two values were the same once the volume of rainfall lost to groundwater (and therefore not converted to runoff) was accounted for.

Unit discharge – from the local subarea:
The unit discharge from each subarea was calculated by dividing the local runoff (sum of the pervious and impervious peak discharges) from each subarea by its area to give a discharge per hectare rate. These values should all lie within a typical range for a 100Yr storm of 9 hour duration, of between 0.2 and 0.3 m^3/s/ha, with variation inside this range being due to spatial differences in rainfall and differences in area and impervious cover (larger sub-areas having lower unit discharges and more impervious sub-areas having higher unit discharges). As is apparent in Figure 4.2.8a the vast majority of local unit discharges do lie in the 0.2 to 0.3 m^3/sec/ha range. Some slightly lower rates are evident from the larger undeveloped subareas in the south eastern quarter of the model and some slightly higher rates in the small subareas in the central portion of the model..

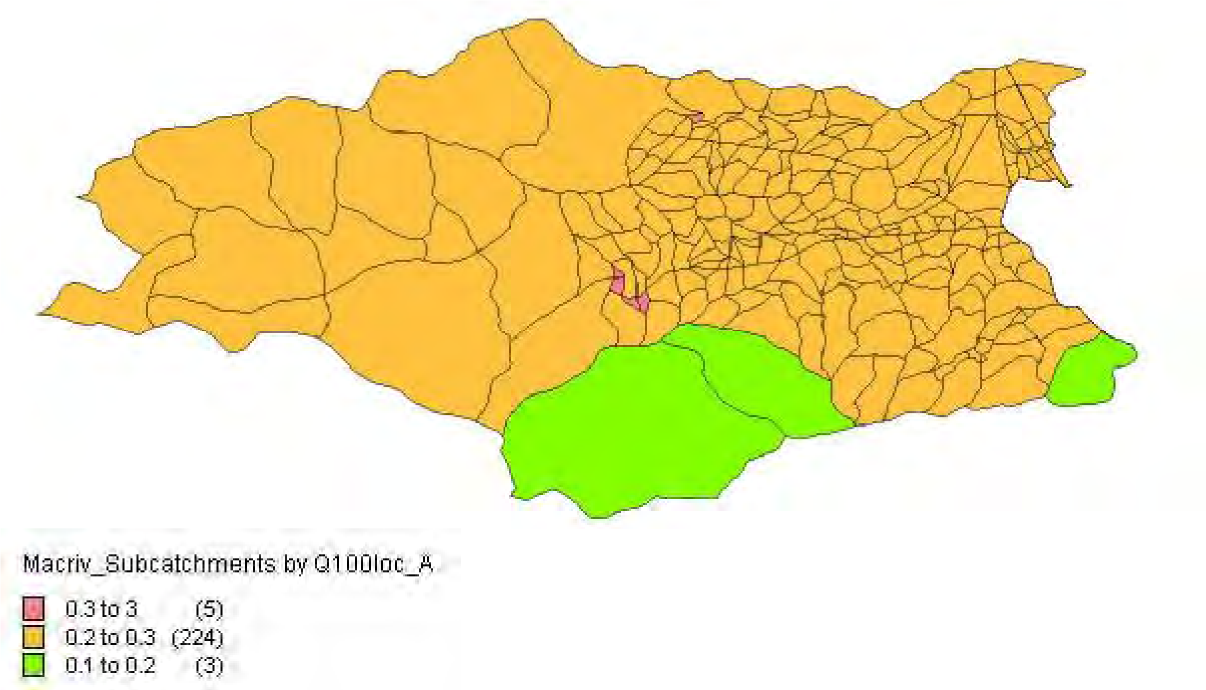


Figure 4.2.8a Peak Local Unit Discharge (m3/s/ha) 1% AEP Event

Unit discharge - cumulative

The cumulative unit discharge at each subarea's outlet was calculated by dividing the total flow at each outlet node by the cumulative contributing catchment area. These values should also lie within a typical range for a storm of this intensity and duration falling on a naturally connected catchment without abnormal storages or diversions (as previously, of the order of 0.2 to 0.3 m3/sec/ha).

Consideration of changes in the magnitude of cumulative unit discharge allow checks to be made on the modelled rainfall distribution, influence of stream routing, attenuation due to basin storage and increases in discharge due to diversion.

Natural subareas at the upstream (western) end of this catchment should (in a correctly constructed model) have higher cumulative discharge rates than their easterly counterparts as rainfall intensities are higher and less stream routing has occurred. Subareas downstream of built up areas should have higher discharges than from neighbouring natural areas. Subareas downstream of large storages should, all else being equal, have lower cumulative discharge rates due to attenuation of peak flow by these storages. Subareas receiving significant diversion should, all else being equal, have higher cumulative discharge rates (sometimes substantially above the natural range), since these subareas can receive a much greater inflow than the naturally connected upstream catchment would normally deliver.

The cumulative unit discharge patterns shown in Figure 4.2.8b reflects these factors, giving confidence to the model's construction. It is noted that the pattern is again dominated by subareas with total discharge rates in the 0.2 to 0.3 m^3/sec/ha range. There are however some subareas (pink colour). with cumulative unit discharges in excess of 0.3 m3/sec/ha. These are either very small head sub areas with minimal attenuation of runoff or areas receiving diversions from adjoining streams, producing higher discharges than would be expected in a natural topologically connected catchment. Areas with less than 0.2 m3/sec/ha total discharge rates are generally subareas below the large natural head subareas with low local discharge rates evident in Figure 4.8.2a.

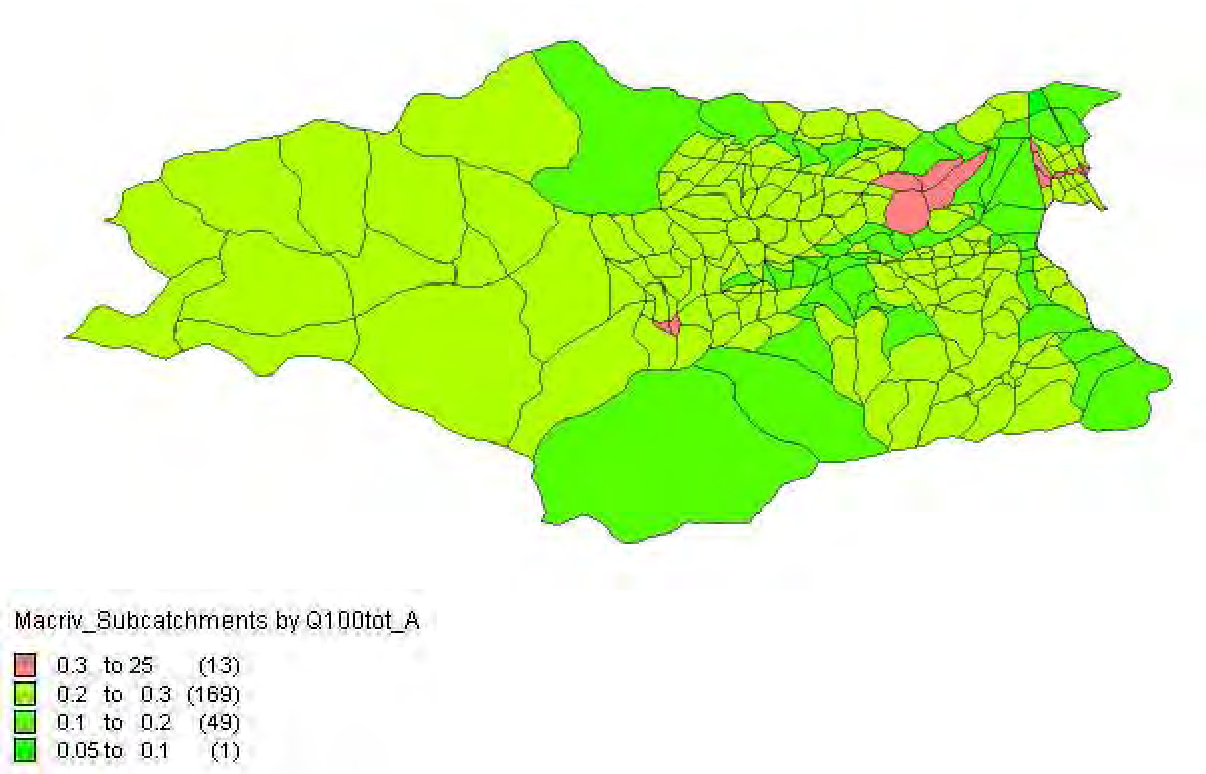


Figure 4.2.8b Peak Cumulative Unit Discharge (m3/s/ha) 1% AEP Event

5 HYDRAULIC MODEL ESTABLISHMENT

5.1 MODEL SELECTION

There are many computer based hydraulic models available today, that have been developed to specifically simulate surface flood behaviour. As noted by Rigby (2005), selection of an appropriate hydraulic model for a particular flooding problem is not trivial, as each of the available models has very distinct strengths and weaknesses. Selection is further complicated by the fact that selection must also consider user skills and possible future uses of the model.

In lesser flood events, Macquarie Rivulet behaves as a 1D system (i.e. flow is generally parallel to the stream centreline and the majority of flow is within or in close proximity to the channel). Several diversions exist for larger flood events, but these diversion flowpaths are mostly well defined and also mostly 1D in nature (such as the diversion along the upstream edge of the railway embankment from Albion Creek back into Macquarie Rivulet). Flood behaviour in larger events, above the Princes Highway and below Albion park village, is however much more complex, involving flow patterns that are far from 1D in nature. In addition there are significant timing differences in peak flows between the various arms that merge on the floodplain above the Princes Highway road bridge, requiring hydrodynamic 2D modelling capabilities to properly quantify the impact of these temporal differences on flood behaviour.

On the basis of the above, It was concluded that a hydrodynamic 2D model would be needed to properly simulate flood behaviour in the lower reaches of Macquarie Rivulet. 2D models are inherently dissimilar to 1D models in that they do not pre-empt flood behaviour by confining flow to individual pre-defined stream 'arms', but instead calculate flow behaviour based on boundary conditions and a three-dimensional representation of the ground surface. Provided close attention is paid to development of an accurate surface representation, (an inherently strong feature of most ALS based 2D models), then very high quality can be achieved in flood modelling. Diversion flowpaths can then be identified directly from 2D flow surface, rather than requiring the modeller to infer behaviour based on a comparison of predicted flood surface with ground elevations.

The model selected as being most suited to the present hydraulic modelling needs, was Tuflow, a grid based two dimensional hydrodynamic model developed by Mr W Symes of WBM Oceanics now BMT WBM . Tuflow has been successfully applied on many similar studies in New South Wales and has significant application both in Australia generally and in several overseas countries, particularly the UK. Tuflow permits incorporation of a wide range of hydraulic structures such as culverts, bridges, weirs and pipe systems into a model and can handle both subcritical and supercritical flows . Further more specific details of the model can be obtained from the website http://www.tuflow.com .

Tuflow is in addition supported by the SMS modelling environment, providing powerful support for both construction of models and viewing of results from a Tuflow simulation. The Environmental Modelling Systems Inc website www.ems-i.com provides further information on this product's capabilities.

5.2 MODEL CONSTRUCTION

5.2.1 GENERALLY

Both Mapinfo and the Surface water Modelling System (SMS) were used to facilitate construction of the Tuflow hydraulic model. Mapinfo is a spatial systems modelling tool produced by the Mapinfo Corporation (USA) and SMS is a hydraulic model building environment produced by the Environmental Modelling Research Laboratory (EMRL) at Brigham Young University. The Tuflow interface was developed by the EMRL in cooperation with the developer of Tuflow, Mr W Symes.

A 7km by 6km 2D grid (domain) based on a 10m cell was chosen to simulate flooding in the area of interest, this being a compromise between model resolution and simulation run time. Since the chosen cell resolution provided a good representation of the waterway of Macquarie Rivulet in larger events, within the study area, the linked 1D (Estry) capabilities of Tuflow were not used to describe the stream network. The 1D facilities were however used to describe the various culverts and smaller bridges with larger bridges being modelled in 2D.

An active zone for the model (a subarea of the 2D grid, within which cells would be included in computations) was initially established by creating a boundary outside of the physical floodplain using the ALS data and aerial photography to define this boundary. This initial active zone boundary was further refined once a Tuflow PMF run had confirmed the 'active' model extents. The model domain boundary and active cells boundary are reproduced in Figure 5.2.1 and at a larger scale in **Appendix D1**.

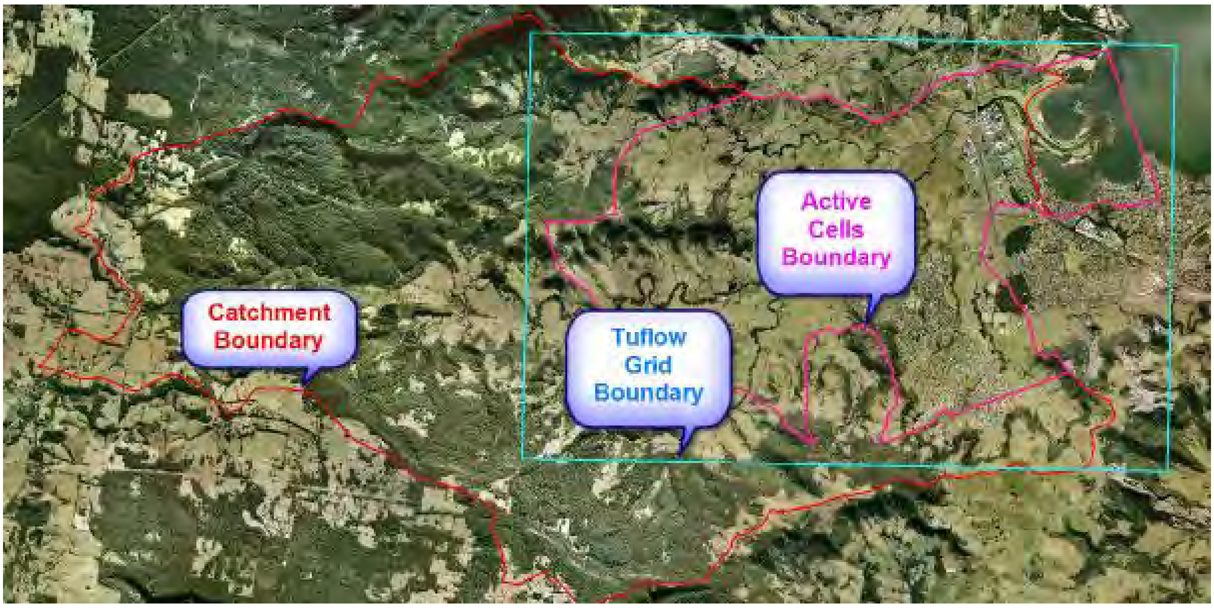


Figure 5.2.1: Model Grid & Active Zone Extents

5.2.2 SURFACE ROUGHNESS

Areas having different properties with respect to retardance of flow (roughness zones) for channel and overbank floodplain areas were identified using Council's zoning data in conjunction with the 2005 high resolution (orthorectified) aerial photography.

Zoning data provides a logical basis for initial discretisation of roughness zones since the physical properties of urban land surfaces are correlated with their usage. For example roads (smooth) and residential areas (rough) have very different roughness properties nevertheless the boundary between them is well defined in the zoning data.

It is noted however that within each Council zone there may be areas of non-typical roughness for that zone. For example, open space zoned land can comprise mown grass (low roughness) or dense forest (high roughness). In addition, roughness can vary within a given zone (for example a mix of grassed areas and forest in an open space zone Council's zoning data therefore required further segmentation to account for these differences. This was achieved by reference to aerial photography and digitization of non-typical areas using tools available in SMS. The various surface roughness zones applying within the active zone of the model are reproduced below in Figure 5.2.2 and at a larger scale in **Appendix D3**.

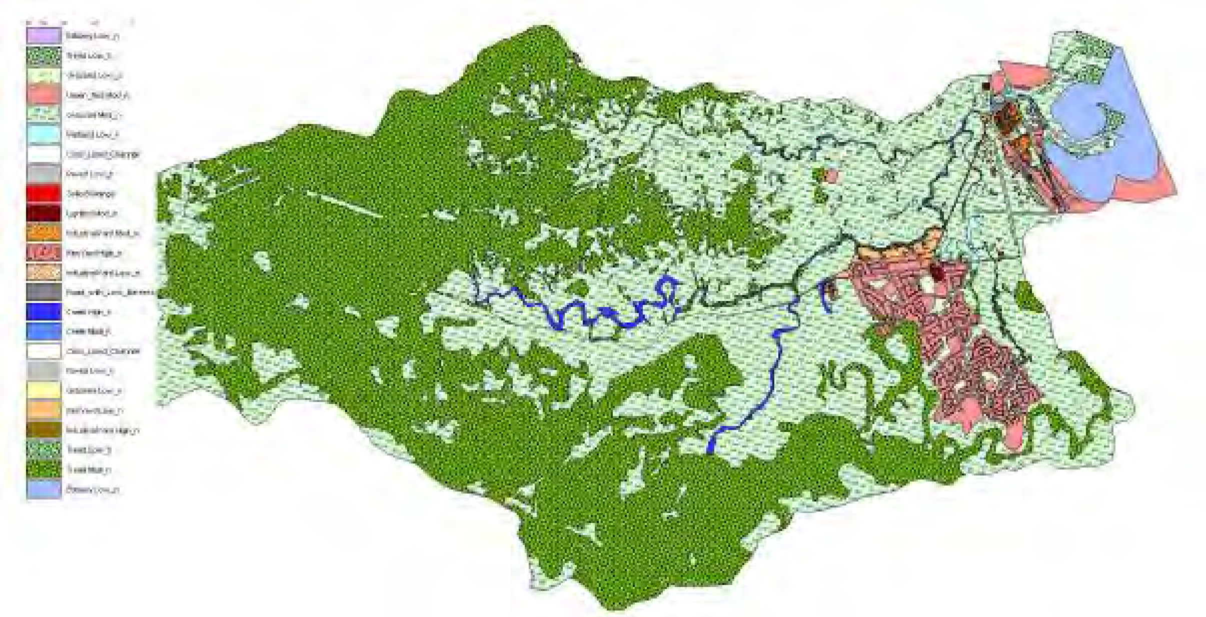


Figure 5.2.2 Hydrodynamic Model Roughness Zones(2009)

Once the surface roughness zones were categorised and mapped, each of the roughness zones was ascribed roughness characteristics. The values initially used for model establishment were derived from consideration of various industry recommendations (including Chow (1959), Hicks *et al* (1991) and Arcement *et al* (1984)), further adjusted to account for local conditions and RIENCO's experience in previous 2D modelling in the Illawarra. For roughness zones such as residential and light industrial where industry consensus values are difficult to find, field inspection and hand calculation of the percentage of flow path blocked by large roughness elements (buildings and fences etc) were used to scale values of roughness for these partly-blocked zones.

The values initially used by the model were further adjusted as part of the calibration process described in **Section 6**. The final values adopted have also been tabulated along with other hydraulic design parameters in **Section 6**.

It is noted that slightly lower roughness values from those used in 1D modelling are appropriate in a 2D model, as the 2D model directly accounts for viscosity and eddy losses, whereas 1D models only incorporate viscosity and eddy losses by including them into a slightly higher 'n' value.

5.2.3 TOPOGRAPHY

The topography of the model was built by using interpolation to project the merged (ALS and bathymetry) elevation scatterset onto a 2m cell size model grid using tools available in Vertical Mapper (a companion product to Mapinfo).

Once the 2m grid had been elevated in this manner, the model surface was inspected to confirm that it was comparable with that of the merged scatterset from which it was derived and, in particular, levels obtained from ground survey.

The resulting model surface, shown reproduced in Figure 5.2.3 and at a larger scale in **Appendix D2**, was found to be a good representation of the original merged scatterset surface and available ground survey levels.

.

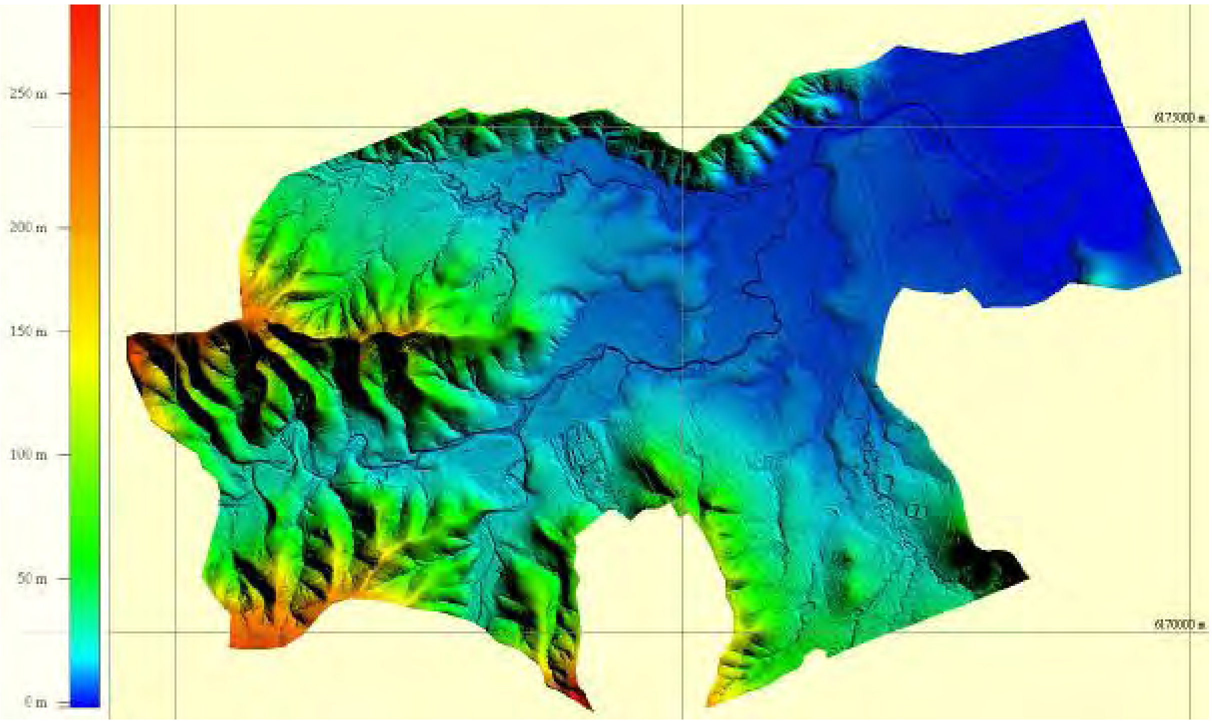


Figure 5.2.3: Hydrodynamic Model Topography

5.2.4 STRUCTURES

All significant structures, including road and railway culverts and bridges, within the study area were incorporated into the model. Geometric details of structures were obtained from existing survey data, augmented by survey undertaken by registered surveyor David Yates, and survey by Cardno Forbes Rigby as described in **Section 3**.

Each bridge was modelled as a 2D structure. In this form, the model surface through the structure is that of the creek and overbank areas between abutments. Additional data is provided for the bridge obvert level (at which pressure flow commences) and the overtopping geometry (at which weir flows commence over the bridge). No expansion or contraction losses are required as the 2D model explicitly accounts for losses associated with flow transitions and misalignment. Some minor form losses are however typically required to reflect pier losses. The recommendations of the User Manual were followed in this regard.

All other structures (culverts) were modelled as 1D elements in which the surface through the structure is that of the embankment or road over, with flow between cells upstream and downstream of the embankment calculated using empirical equations as described in the Tuflow User Manual.

All structures were initially modelled fully clear (i.e. no blockage).

5.2.5 TRUNK DRAINAGE NETWORK

There is no trunk drainage network that could influence flooding in the study area, As such a linked 1D/2D model of the underground network was not required in this model.

5.2.6 BOUNDARY CONDITIONS

Two classes of temporally variable boundary conditions were applied in this model.

1. Inflow hydrographs (both on the upstream boundary and internally to the model)
2. Tailwater levels (at the models downstream boundary (Lake Illawarra))

The locations at which these various boundary conditions were applied are shown graphically in **Appendix D5**.

These conditions are discussed further in **Section 6** (Model Calibration) and **Section 7** (Design Flood Hydrology)

5.2.7 PRELIMINARY MODEL CHECKS

Once constructed, the preliminary hydraulic model was run with the 1%AEP design flows from the hydrology model assuming all structures to be clear. The primary purpose of this initial run was to confirm model stability and the reasonableness of results obtained. Where data was available, a comparison was made with previous model results to confirm that the preliminary model for the current study was providing results within the expected range.

Once preliminary model checks were completed the model was then modified to reflect conditions in 1991 and calibrated to the June 1991 event in accordance with the methodology described in **Section 6**.

6 MODEL CALIBRATION AND VALIDATION

6.1 CALIBRATION & VALIDATION METHODOLOGY

Model calibration is required to confirm the ability of a hydrologic/hydraulic model to simulate recorded flood behaviour from recorded rainfall. Calibration involves building a model using recorded data from a historic storm and comparing predicted results with recorded results, then making adjustments to the model(s) (if necessary) to minimise differences. It was identified during the data collection phase of the current study that reliable data for such calibration was available for the June 1991 event. This information included;

- Historic flood levels from the event of June 11th 1991 in the form of continuous stage records (CSRs) at two gauges, Maximum Height Indicator (MHI) readings at six locations and a number of peak flood levels obtained by survey of debris and flood marks left after the event.

- Water levels for lake Illawarra over the relevant time period

- Coincident June 1991 rainfall data at five minute intervals from five rainfall gauges within the catchment,

- Co-incident information with respect to the model catchment conditions, level of development and presence of infrastructure in the floodplain at the time of the event

Using this data, hydrology and hydraulic models were constructed, run and their results reviewed. Where justifiable, model parameters were adjusted to ensure closeness of fit between modelled and recorded discharges and flood levels. It is of importance to note that the presence of CSRs in the catchment permitted the calibration of the hydrologic and hydraulic models to proceed independently. This (rather rare in the Illawarra) circumstance all but eliminates concerns as to whether the coupled hydrologic/hydraulic models are producing a good event simulation as a consequence of opposing errors in the calibration of each model.

6.2 CALIBRATION EVENT OF JUNE 1991

6.2.1 GENERALLY

Over the period 6th to 14th June 1991, a low pressure system moving south from Queensland, and a high pressure system fairly stationary in the Tasman Sea directed humid easterly air onto the South Coast of NSW, causing heaving rainfall over a 6 day period. This heavy rainfall caused minor to moderate flooding throughout the Wollongong area, particularly in the Lake Illawarra/Macquarie Rivulet catchments.

As previously noted, rainfall during this event was recorded at five gauges (5minute resolution), flood levels were recorded at two CSRs , six MHIs and at several points from survey of flood marks left after the event. While the CSRs now operating in Lake Illawarra had not been installed at this time, several readings were made of lake stage by the SES at different times, providing reasonable definition of the variation in Lake stage during the event. Flood marks, surveyed around the Lake after the event, confirm the sensibility of these observed Lake levels.

6.2.2 AVAILABLE DATA

The rainfall event was recorded by 5 gauges located within the catchment.

- Macquarie Pass(Glover Hill) (MHL)
- North Macquarie (MHL)
- Yellow Rock (MHL)
- Upper Calderwood (MHL)
- Albion park (SW)

A hyetograph of rain falling during this event at Macquarie pass and an analysis of burst IFD for the same gauge is reproduced in Figure 6.2.2a. Comparable plots for all gauges operating during the event in the catchment, are reproduced in **Appendix B5**.

.

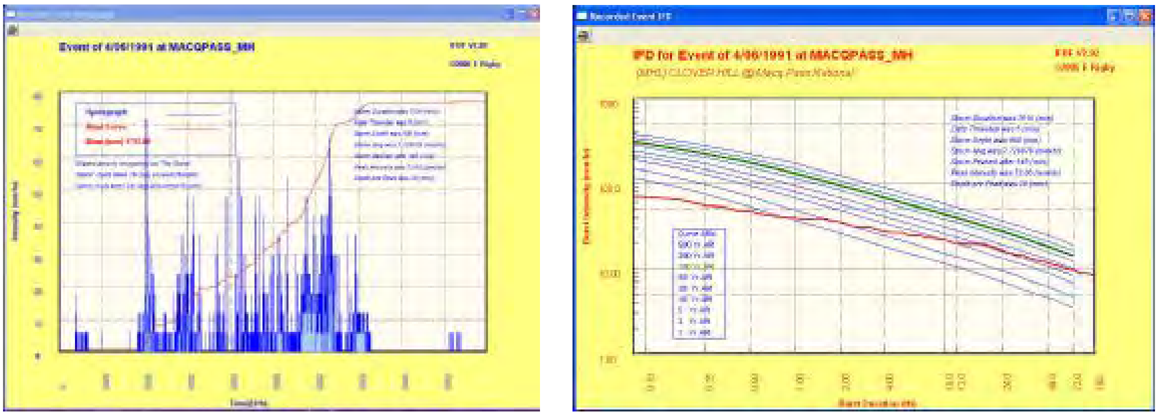
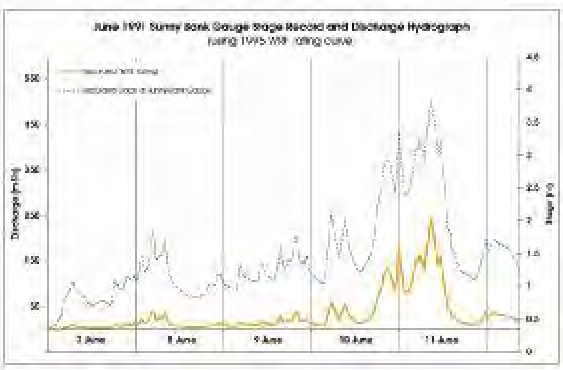


Figure 6.2.2a: Hyetograph & IFD –Macquarie Pass - June 1991

The variation in flood stage during this event was captured at the Albion Park (Sunnybank) CSR and also by the Princes Highway CSR. Traces for both gauges are reproduced below in Figure 6.2.2b and at a larger (full page) scale in **Appendix B6** and **Appendix B7**. The lake stage hydrograph based on SES observations is also included on the Princes Highway Gauge trace. The discharge hydrograph at each gauge, based on the WRF rating curves, is also included on each plot.



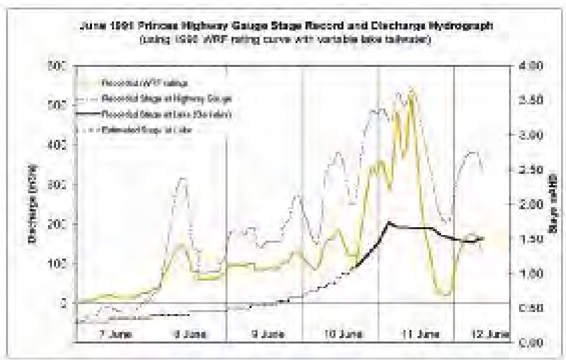


Figure 6.2.3b: Albion Park and Princes Highway CSRs – June 1991

6.2.3 MODEL CALIBRATION

Using the collected data, hydrologic and hydraulic models were constructed in order to represent flood behaviour within the study area during the June 1991 event.

The 'core' hydrologic model was modified to incorporate rainfall data recorded during the event as measured at the five gauges. Model parameters and losses were initially as described in **Section 4**. During the calibration process it was found that while the hydrologic model was simulating peak discharges well, predicted flows at the commencement of the event were far too high. Initial loss was therefore increased until the simulated early discharges correlated reasonably with those recorded. This required an increase in initial loss for the June 1991 event to 150mm.

A comparative plot of the hydrographs as derived from stage records and simulated at each of the two CSRs is reproduced in Figure 6.2.3a. and at a larger scale in **Appendix E1** and **Appendix E2**. Given the excellent correlation in magnitude, timing and slope of the rising and falling limbs of the hydrographs at the two stations, no change was made to any of the other model parameters.

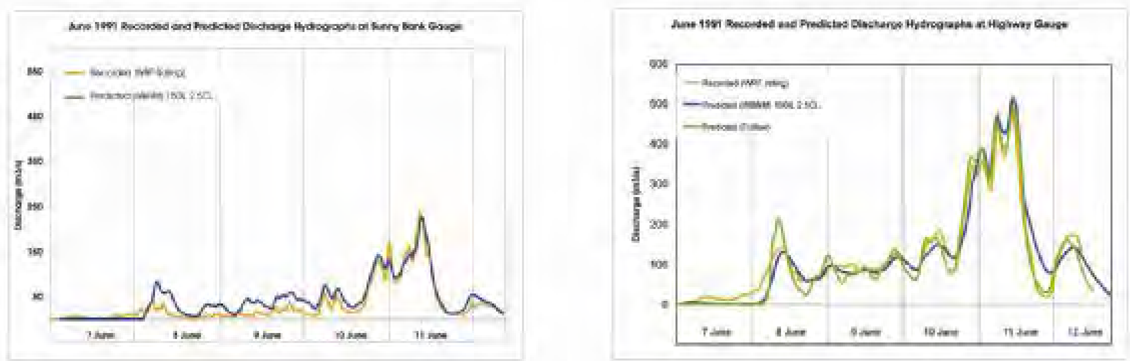


Figure 6.2.3a : June '91 Discharge Hydrographs – Sunnybank & Princes Hway CSRs

The adopted June 91 hydrologic model parameters were then;

Initial Loss (IL perv)	150mm
Initial Loss(Il Imp)	1mm
Cont Loss (CL:R)	2.5mm/hr
Catcment Lag (C)	1.3
Imp Lag Factor	0.1
Stream Lag Factor	1.0
Init Storage Levels	Dry

Peak discharges for the June 1991 event extracted from the calibrated hydrologic model at previously modelled locations were;

Table 6.2.3a: Peak Discharges at Selected Locations –June 1991event

Location (WBNM 2009 Subarea)	Qp PSxRM WRF 1996	Qp WBNM WRF 1996	Qp WBNM Rienco 2009	Gauged WRF rating
Sunnybank CSR (MacRivEBot)	290	270	245	241
Macriv DS Calderwood Rd (MacRivUBot)	420[1]	370[1]	260	-
Marshall @ Grey Meadows (MarsHTop)	120	90	99	-
Frazers DS Tongarra Rd (FrasITop)	90	80	64[2]	-
Tara DS Tongarra Rd(TaraGTop)	-	-	32[2]	
Princes Hway CSR (MacRiv1Top)	575[1]	516	517	520

1. *Earlier models did not incorporate the significant abnormal storages or diversions that developed in this event*
2. *Tara and Frasers Ck flows need to be combined to relate to the earlier modelled flows.*

Following acceptable calibration of the hydrology model, the 'core build' (present conditions) hydraulic model was modified to incorporate known changes to the surface topography and roughness that occurred between June 1991 and the present. These modifications to the 'core' (present conditions) hydraulic model included;

- Lowering of the airport runway back to the levels present in 1991.
- Removal of fill and reconstruction of an area on the northern bank of Macquarie Rivulet, downstream of the Road and Rail bridges, to reflect conditions prevailing in June 1991 (altered post 1991 during construction of a new subdivision in this area).
- Removal of a road embankment and culvert on Albion Creek, downstream of the Illawarra Rail crossing, to reflect conditions in June 1991 (altered post 1991 during construction of a new subdivision in this area).
- Reclassification of some present residential areas back to open space(areas not yet developed in 1991.
- Reclassification of a land parcel on the south bank of Macquarie Rivulet upstream of the Princes Highway to reflect conditions prevailing in June 1991 (now a developed nursery)

No other modifications to the hydrodynamic model were made in the initial calibration run.

The simulated event stage hydrograph at the Princes Highway CSR, is presented in Figure 6.2.3b . In general, good agreement between recorded and predicted peak flood levels was achieved throughout the study area in the first run, except for a few locations where simulated levels were mostly higher than the recorded levels. Minor adjustments were then made to the model surface roughness values, in these areas, to improve the fit. In Figure 6.2.3b the first run calibration hydrograph is shown in yellow and the final calibration hydrograph in red.

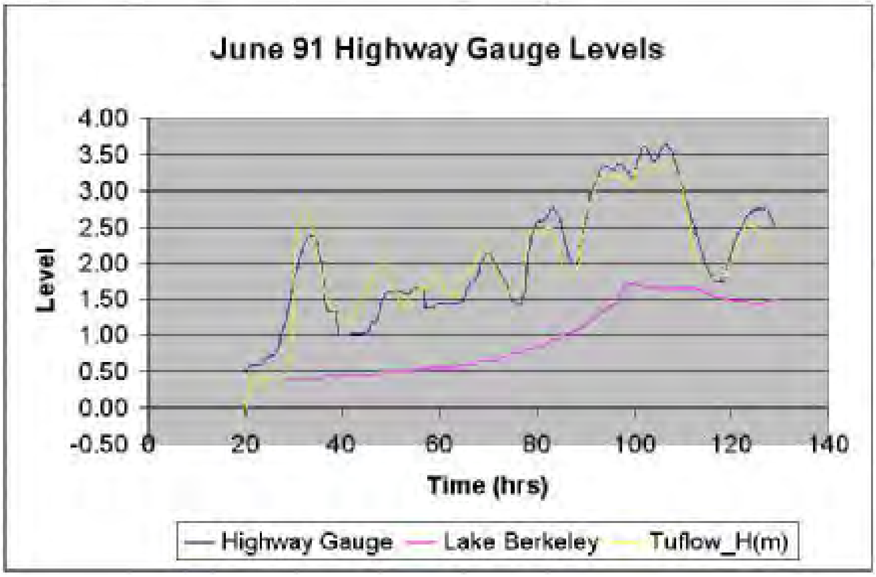


Figure 6.2.3b : June '91 Stage Hydrograph –Princes Hway CSR

The surface roughness values finally adopted are tabulated in Appendix E4. In this table n1 and n2 are the roughness values at depths D1 and D2 respectively. Below a depth of D1, n1 applies and above a depth D2, n2 applies. Between D1 and D2 the surface roughness varies linearly between n1 and n2.

In setting likely error bands for recorded flood levels, two factors in particular were considered;

- The likely difference between the actual flood level and level of the point as surveyed
- The likely difference between the simulated level and actual level due to positional differences between the models floodmark and the actual floodmark

With respect to likely error due to the type of data record, three record classes were defined;

- CSR and MHI records - assigned a base likely error band of ± 0.05m
- Wall Stains and debris on the flood fringe –a base likely error band of ±0.1m
- Debris in trees on fences inside the flood fringe- a base likely error band of ±0.3m

Likely differences due to positional misalignment of the model and record dataset were set at;

- 2m if the flood mark was located at a fixed, well defined (surveyed) visible location
- 10m elsewhere although directionally limited by the description if related to a particular feature (such as along a fence line).

Three classes of flood surface gradient were used to quantify likely vertical error bands from these positional misalignments as set out in Table 6.2.3b..

Table 6.2.3b: Likely Error in Level Due to Positional Uncertainty

Flood Gradient	**Range (m in m)**	**2m Plan Tol**	**10m Plan Tol**
HIGH	> 1m in 20m	±0.10m	±0.50m
MODERATE	Between	±0.05m	±0.25m
LOW	< 1m in 200m	±0.01m	±0.05m

Simulated peak levels and differences from recorded levels for the ‘calibrated’ hydraulic model in the study area are shown in Figure 6.2.3c and at larger scale in **Appendix E.3**. This plot shows the difference between the simulated flood level and recorded flood level on the aerial photo underlay as a coloured bar, located in a calibration target in which the upper and lower extents of the target represent the recorded data likely error limits Simulated levels falling within the likely error band are shown in green. Simulated levels falling in the band between one and two times the likely error are shown in orange and beyond two times the likely error in red. Coloured bars above the mid target line indicate predicted flood levels greater than recorded levels and bars below the mid target line identify predicted levels that are below recorded levels.

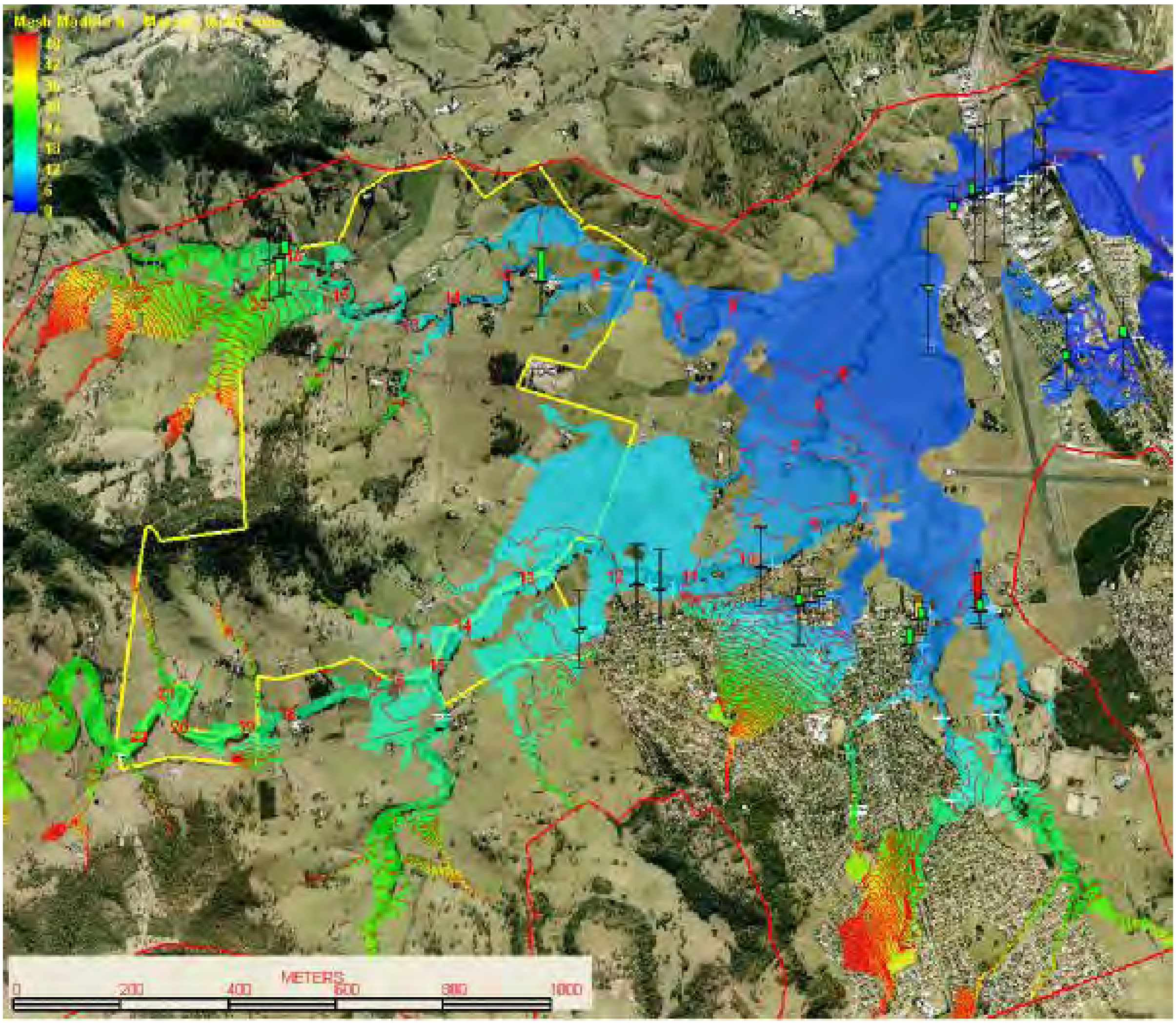


Figure 6.2.3c : Recorded –v- Simulated Peak Flood Levels – June 1991

In setting likely error bands for each recorded flood level, the likely error from the base ‘class’ value was added to the likely error due to positional uncertainty and flood gradient at each location. As is apparent in the target heights, this resulted in a variation in likely total error that varied from about 0.05m to 0.5m.

As modelling in the built up area of Albion Park village did not incorporate consideration of the impact of underground drainage on flood behaviour, no attempt was made to review predicted flood levels against those recorded in this area. In addition some recorded levels in the study area were clearly in error. The two flood levels recorded where Frazers Creek crosses the Illawarra Highway, were isolated debris levels located well inside the flood perimeter at road level. As such they were not indicative of the peak flood level in this area. Flood levels for two lines of debris on the banks of Yellow Rock Creek were on investigation found to be more than a metre higher than the ground level at each location and also discarded from the calibration dataset. A tree debris level near North Macquarie road was found to be more than 5m above ground at a allocation where floodwater could not on practical grounds have been anywhere near that high. Given the proximity to the problematic levels on Yellow rock Creek it seems likely that there was a problem with the survey in this particular area.

The remaining flood levels were considered 'reliable' within the limits of their data class and positional accuracy and used to then calibrate the hydraulic model. As is apparent in Figure 6.2.3c, simulated flood surface levels are, for the most part well within the likely error bands of the reliable recorded data with no higher or lower trends present. It is noted that simulated peak flood levels in Frazers Creek downstream of the Illawarra Highway are noticeably higher than recorded. As no blockage data was available for the June 91 event, all structures were run 'clear'. It seems likely that the structures upstream of these levels blocked in part during the event, throttling peak flow, and in turn reducing peak flood levels downstream of these structures.

The final calibration against the June 1991 flood event is therefore considered particularly good, giving confidence to both the hydrologic and hydrodynamic models' ability to predict flood behaviour in a moderate flood event. Although this does not in itself guarantee predictive accuracy for much larger events, both the hydrologic and hydrodynamic models are based on widely accepted parameter values (used for other similar catchments in the Illawarra) and have been independently calibrated. Reasonable accuracy in the simulation of larger events can therefore be expected.

6.3 MODEL VALIDATION

As only one event dataset was considered sufficiently comprehensive and reliable for calibration/validation purposes, an independent validation run was not possible.

Given that the event did however engage most of the lower floodplain of Macquarie Rivulet and its tributaries and the hydrologic and hydraulic models were able to be independently calibrated, the concerns normally associated with extrapolation of event magnitude in coupled hydrologic/hydraulic models are not as significant as they might otherwise be.

We are therefore confident that the model can and will provide an accurate simulation of flood behaviour in a 1% AEP event and be as accurate as is ever the case in a PMF event.

7 DESIGN FLOOD ESTIMATION

7.1 DESIGN FLOODING CONSIDERATIONS

7.1.1 DESIGN RAINFALL

Standard hydrologic modelling procedure as set out in AR&R (1987) calls for the selection of a critical storm 'burst' duration that maximises discharge at a particular location. This procedure assumes that a critical 'burst' of given ARI will, all else being average, produce a flood peak discharge of comparable ARI. This approach does not account for two major differences between real storms (from which this procedure was derived) and design bursts:

1) Initial losses applicable to a short duration design burst are unknown (often assumed zero)

2) Short duration design bursts can not account for the effects of lead up rainfall on stream flows and accumulated flood storage, at commencement of the design event.

To overcome these concerns, the approach proposed and adopted for this study is to embed a design burst within a much longer 'envelope storm'. A 36 hour AR&R design storm was selected as an envelope storm since this is within the duration range of typical flood producing events in the region and also corresponds to the duration of the design storm event used in modelling carried out for Lake Illawarra as described in the Lake Illawarra Flood Study (Lawson & Treloar, 2001). This then provides a logical basis for selecting an appropriate tailwater condition where Macquarie Rivulet enters the lake, since the same overall design storm duration is used on both the lake and Macquarie Rivulet catchments (refer **Section 7.1.4** for further discussion).

The Embedded Design Storm (EDS) procedure for embedment of a burst within an envelope storm has been described by Rigby et al (1996, 2003, 2006). The EDS procedure described involves positioning the burst within the storm such that the peak of the burst and peak of the envelope storm coincide. The burst is used to replace the storm where they overlap. In order to maintain the overall volume of the envelope storm, the wings of the envelope storm outside the burst are lowered on a pro-rata basis.

The paper by Rigby *et al* (2003) points out that where a catchment's critical duration is much less than the duration of typical flood producing storms in the area, and a catchment's critical burst duration is less than about six catchment lags, then the standard AR&R 'burst only' design flood estimation procedure will begin to underestimate peak flows when compared with historical storms of similar frequency and peak intensity..

The EDS procedure "'warms up' a catchment in a logically derived manner, eliminating for the most part, potential errors introduced by the AR&R design procedures lack of recognition of the influence of lead rainfall on burst response" (Rigby *et al*, 2003).

Application of the EDS procedure will also generate a more realistic hydrograph with a duration similar to that associated with historic storms, This provides more realistic estimates of periods of overtopping or inundation than those obtained from the AR&R 'burst only' based procedure.

The following should also be noted with respect to the EDS procedure:

- The burst duration producing minimum error when embedded into a storm is often shorter than the critical burst duration that would normally be derived using the standard AR&R approach. This occurs since the embedded storm lead rainfall is sufficient to create part full storages prior to the burst. In the standard AR&R approach, burst duration often needs to be extended before flow can be maximised as runoff is still filling storages.

- PMP bursts cannot be embedded within PMP envelope storms of duration greater than 6 hours since the techniques for Probable Maximum Precipitation using the Bulletin 53 Generalised Short Duration Method (GSDM) extend only to 6 hours. Therefore the PMF embedded design storm used for the current study was a 36 hour, 500 year ARI storm built from standard AR&R IFD and temporal pattern data. It is noted that the effect of this envelope of smaller size (greater frequency) with respect to the burst can be ignored since the results are relatively insensitive to the volume of the envelope storm once a storm is sufficiently large to fill storages prior to the peak.

- It is acknowledged that the overall embedded design storm concept does not fall within current standard industry procedures and is not documented in the current version of Australian Rainfall & Runoff which is essentially a re-printed version of the Institution of Engineers 1987 publication. However, AR&R is currently undergoing major revision and it is understood that recommendations with respect to embedded design storms will be included in the next release (expected some time around 2012). It was however felt that given the considerable benefits of using the embedded design storm procedure in any catchment, that the current study should be proactive and apply the procedure to ensure its currency and validity is maintained after the imminent AR&R revision.

To establish the 'critical' burst duration to embed, a series of 1% AEP bursts of varying duration were embedded in a 1% AEP 36 hour envelope and peak flows in the vicinity of the study area compared. A burst of 9 hrs, embedded in the 36 hour envelope was found to maximise flows through the study area.

7.1.2 ANTECEDENT CONDITIONS AND STORM LOSSES

It is noted that when using the AR&R bursts based procedure for design flood estimation, a value of 0 mm is typically used as an initial loss. However the use of an embedded design storm requires use of higher (realistic) initial losses. For the purpose of hydrologic modelling of 'design' events a 15mm initial loss of rainfall was adopted based on initial losses recorded by Cordery & Webb (1974) in real events across NSW.

A 2.5mm per hour continuing loss was applied to rainfall for the duration of the storm, reflecting both a typical value for continuing loss used in design modelling in the Illawarra and the value obtained from calibration of the June 1991 storm event.

7.1.3 BLOCKAGES AND DIVERSIONS

The current study has incorporated the effect of culvert and bridge blockage on design flooding by directly modelling the obstruction caused by blockage at key structures. This required the establishment of blockage levels (percentage of opening) to be applied to the study. In consultation with Shellharbour Council and the Horsley Creek Floodplain Risk Management Committee, the blockage levels set out in Table 7.1.3 were adopted for the adjacent Horsley Creek catchment. As Shellharbour Council has not yet adopted a formal blockage policy and the Wollongong Council policy was derived from much steeper catchments to the north, the Horsley Creek design blockage levels have been adopted in this study.

Table 7.1.3: Blockage levels applied to this study

Type of Structure	Blockage Level Assumed
Multiple inlet trunk systems where combined street drainage inlet capacity >>> barrel capacity	assumed clear (0% blocked) throughout the event
Smaller culvert/bridge systems (<1500mm diagonal opening or with either height or width less than 1000m)	assumed 100% blocked at peak of storm
Larger culvert/bridge systems (>= 1500mm diagonal opening)	assumed 20% blocked at peak of storm

As well as the level of blockage, the modelled pattern of blocked structures across a catchment must also be considered. Where blockage of a particular structure influences the size of a diversion occurring at the structure, blockage will increase flood levels along the diversion flowpath (and any receiving downstream reach), whilst at the same time decreasing flood levels in the directly connected reach immediately downstream of the structure. Two alternate blockage patterns therefore need to be modelled as a minimum: 'all clear'; and 'all blocked'. Where there are two or more structures within adjoining catchments linked by diversion, a combination of clear and blocked structures or 'mixed' blockage pattern may also need to be considered. In highly complex catchment systems, it is possible that more than one mixed blockage pattern will need to be investigated since some patterns cannot be modelled concurrently. However when establishing the mixed blockage patterns to be modelled, consideration needs to be given towards the likelihood of the particular pattern being considered to avoid improbable combinations.

For design event modelling in the present study, both the 'all clear' and 'all blocked' patterns were initially modelled. The 'all blocked' pattern was however found to generate maximum flooding both through and in the vicinity of the site, allowing the 'all clear' scenario to be dropped from further consideration.

Results from the all blocked condition were used to establishing peak flood behaviour through and in the vicinity of the site. Flood levels, velocities, depths, unit flow and the NSW FPDM hazard surfaces presented in this report represent the maximum modelled results, throughout each event.

7.1.4 LAKE LEVEL

Flooding can occur in the lower reaches of Macquarie Rivulet (the area generally downstream of the weir in Macquarie Rivulet) via two mechanisms:

- Lake flooding due to elevated water surface levels in Lake Illawarra
- Riverine flooding due to elevated water surface levels in Macquarie Rivulet

Whilst both modes of flooding (lake and riverine) can and will occur to some extent during a single storm, it is unlikely that:

1) Both the lake and creek would experience maximum flood levels of the same ARI during a single event
2) That these maximums would occur at the some point in time.

This reflects the disparate hydrologic characteristics of Lake Illawarra (large catchment, slow response) and Macquarie Rivulet (smaller catchment with faster response).

For the purpose of design event modelling, a temporally variable tailwater condition needs to be established for the downstream boundary of the hydrodynamic model. Given the low probability that lake and riverine flood levels would peak at the same instant in time, a methodology is needed that reflects this temporal separation.

A tailwater condition in Lake Illawarra was therefore adopted that could be 'expected' to occur simultaneously with flooding in Macquarie Rivulet. This involved a procedure in which;

1) The Lake Illawarra stage hydrographs for the 5%, 1% AEP and PMF events (as modelled by Lawson & Treloar), were obtained. These differ slightly from those used in the Lake Illawarra Flood Study, as the lake model was upgraded by Lawson & Treloar following completion of the flood study.

2) For each design event modelled, the lake hydrograph, of equivalent ARI to the modelled stream event, was applied as a dynamic boundary condition along the downstream boundary of the hydraulic model domain. The temporal relationship between the lake and stream hydrographs was established by aligning the peak of the (36hr) storm causing Lake Flooding with the peak of the (36hr) Embedded Design Storm being applied to the Macquarie Rivulet catchment. This is considered a conservative approach as differences in the rainfall mechanisms causing peak lake flooding of a given ARI and stream flooding of the same ARI would probably not lead to events of comparable ARI simultaneously in both systems. It is however likely that heavy rainfall on the Lake and its contributing catchments would coincide with similarly heavy rainfall on the Macquarie Rivulet (itself part of the contributing catchment to the Lake).

In Figure 7.1.4, the supplied lake stage hydrograph is plotted on the same base as the Macquarie Rivulet stage and discharge hydrograph for the 1%AEP event at the Princes Highway road bridge. This plot shows the relationship of peak runoff in Macquarie Rivulet with Lake stage, highlighting the temporal separation of flood peaks between the two systems.

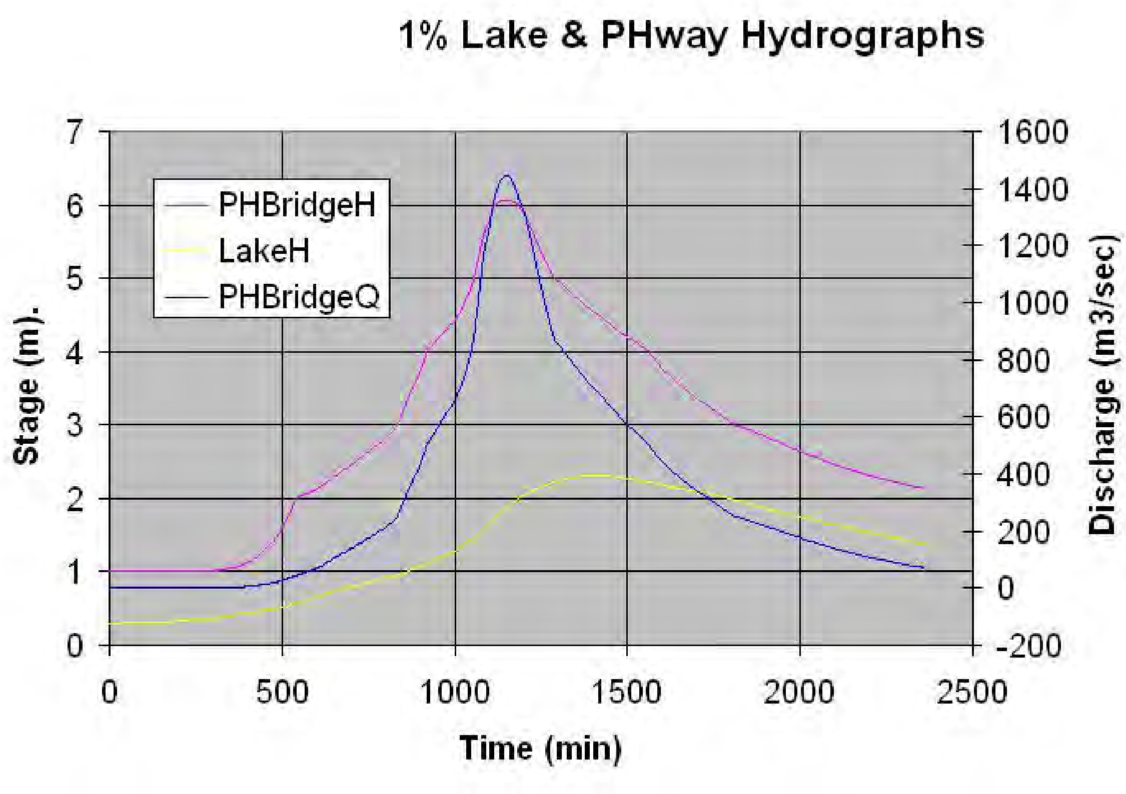


Figure 7.1.4: Lake Illawarra and Macquarie Rivulet 1%AEP Hydrographs

It is noted that the positioning of the Macquarie Rivulet hydrograph relative to the Lake Illawarra hydrograph was facilitated by the use of the same envelope storm duration as the critical storm applied to Lake Illawarra (i.e. 36 hours). It was simply assumed that the two storm hyetographs commenced at the same time, allowing the appropriate lake level at any point in time to be directly read from the Lake hydrograph. This is a transparent and logical approach which can be repeated for studies in other creeks affected by lake flooding. This approach is analogous to both the lake and inflowing catchments responding to a storm with similar temporal patterns.(a likely occurrence).

It is again noted that it would be unlikely that in an event that maximises flow in Macquarie Rivulet, that lake flooding would also be maximised. The lake stage hydrograph in Figure 7.1.4 for example would most likely peak at a level significantly lower than that shown in a 1% AEP event in Macquarie Rivulet. The approach adopted, which assumes the lake's hydrograph is at least on its way towards an event of comparable severity is therefore considered conservative.

7.2 DESIGN FLOOD HYDROLOGY

7.2.1 ADOPTED HYDROLOGIC DESIGN PARAMETERS

This section provides a summary of adopted hydrologic design parameters used to establish design peak discharge estimates within the catchment. Equivalent details for the hydraulic model are presented in **Section 7.3**.

As described in **Section 7.1** an Embedded Design Storm (EDS) approach was adopted for the current study. A 'critical duration' burst was embedded within an envelope storm, with both the burst and envelope storms being derived from standard AR&R IFD data and temporal patterns.

The 'critical' burst duration was selected as 540 minutes based on an analysis of all standard AR&R durations between 1 hour and 12 hours. The 9 hour (540 minute) burst embedded within the 36 hour envelope storm was found to generate maximal discharge in the mainstream of Macquarie Rivulet adjacent to and downstream of the proposed development site.

This 540 minute burst was embedded within a 36 hour envelope storm as described by Rigby et al (1996). The 36 hour storm envelope was selected since this event is the same duration as the event used for modelling flooding in Lake Illawarra and is within the range of typical flood producing events in the region and can therefore provide a realistic lead up rainfall condition.

A total of three design gauges were used, with locations as shown on the plan included in **Appendix A.7.** . Figure 7.2.1 below shows the 1% AEP design EDS (9hr in 36 hr) hyetograph at the design gauge named "Macriv#1" located in the central part of the catchments. Other gauges have the same temporal pattern but are based on slightly different IFD data reflecting spatial variation in this data across the catchment.

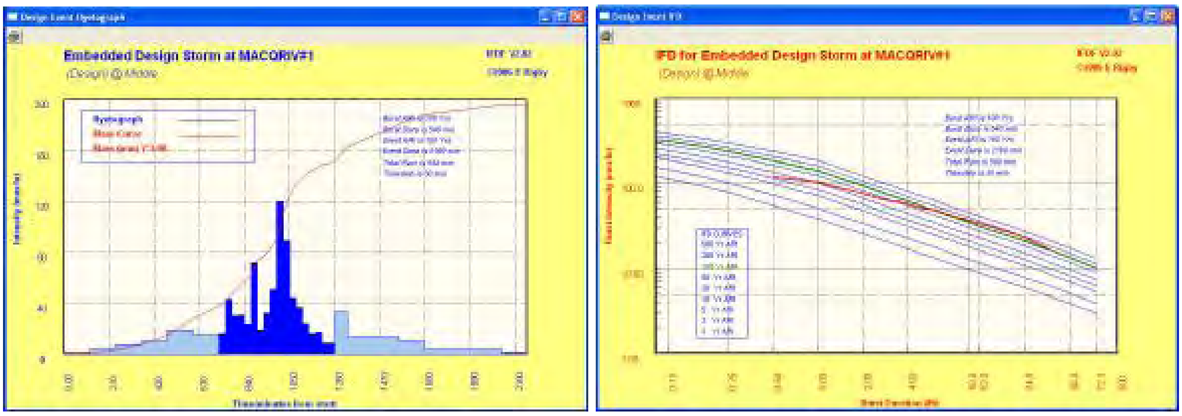


Figure 7.2.1: Design EDS Hyetograph & IFD at Design Gauge "Macriv#1"

All storages in the model were assumed to be empty at the beginning of the event. It is noted however that through use of the EDS design rainfall procedure, storages will contain some flood water prior to the AR&R burst. The volume of floodwater will have been calculated in a logical manner by the model and will account for the specific hydrologic and hydraulic characteristics of each storage and their contributing catchments.

The following Table 7.2.1 provides a summary of other adopted hydrologic design parameters used to establish design peak discharge estimates within the catchment. Further description of each parameter and its role is provided in **Section 4.2.6**.

Table 7.2.1 Adopted Design Hydrologic Model Parameters

Hydrologic Parameter	**Value Adopted**
Catchment Lag 'C'	1.3 globally
Impervious Lag	0.1 globally
Stream Lag	1.0 Natural Stream condition 0.5 Grass Swales 0.33 Roads and Concrete Channels Time delay (no routing) of 0.5 minutes for all small sub-areas (~0.1ha)
Losses Initial Loss (IL)	15 mm
Continuing Loss Rate (CLR)	2.5 mm per hour

7.2.2 HYDROLOGIC MODELLING RESULTS

The following Table 7.2.2 provides a summary of design peak discharges for the 1% AEP and PMF events at selected locations within the catchment. These peak discharges are not coincident in time therefore the times at which these peaks occur (relative to the commencement of rainfall) have also been provided.

Table 7.2.2: Summary of Design Peak Discharges at Selected Locations

Location	**Peak Discharge (m^3/s)**			**Time to Peak (min)**		
	20%AEP	**1%AEP**	**PMF**	**20%AEP**	**1%AEP**	**PMF**
Macriv@SBank Gauge (MacRivE -Bot)	332	656	1313	1075	1070	1120
Macriv DSCalderwood Rd(MacRivU-Bot)	378	696	1398	1120	1090	1135
Marshall DS Marshall Mt Rd (MarsD-Top)	128	268	528	1060	1055	1105
Frazers DS Tongarra Rd (FrasI –Top)	116	130	294	1075	1060	1092
Tara DS Tongarra Rd(TaraG-Top)	33	63	136	1050	1050	1075
Town DS Ill	15	27	57	1025	1020	1055

Hway(TownH-Top)						
Hazleton[1] Ds Ill Hway(HazeF-Top)	40	78	174	1060	1050	1090
Yellowrock DS Ill Hway(YellF-Top)	133	277	602	1075	1065	1125
Macriv@PHwayGauge (MacRiv1Top)	601	1424	2249	1210	1155	1165

1. *Also shown on mapping as Cooback Ck*

7.3 DESIGN FLOOD HYDRAULICS

7.3.1 HYDRAULIC DESIGN PARAMETERS

While the topographic and roughness data are those applicable in 2009 (modified from those applying in 1991 for the calibration event), all other hydraulic model parameters were as discussed in previous sections and applied in calibration modelling.

7.3.2 HYDRAULIC BOUNDARY CONDITIONS

Boundary conditions applied in design event modelling were;

- The downstream lake stage hydrograph for a 36 hour storm event
- The various total and local inflows to the model from a 36 hour storm event

7.3.3 HYDRODYNAMIC MODELLING RESULTS

The following Table 7.3.3 provides a summary of design flood levels for the 1% AEP and PMF events at locations of interest. The values included in the table represent the maximum levels occurring at each location, in an 'all policy blocked' scenario.

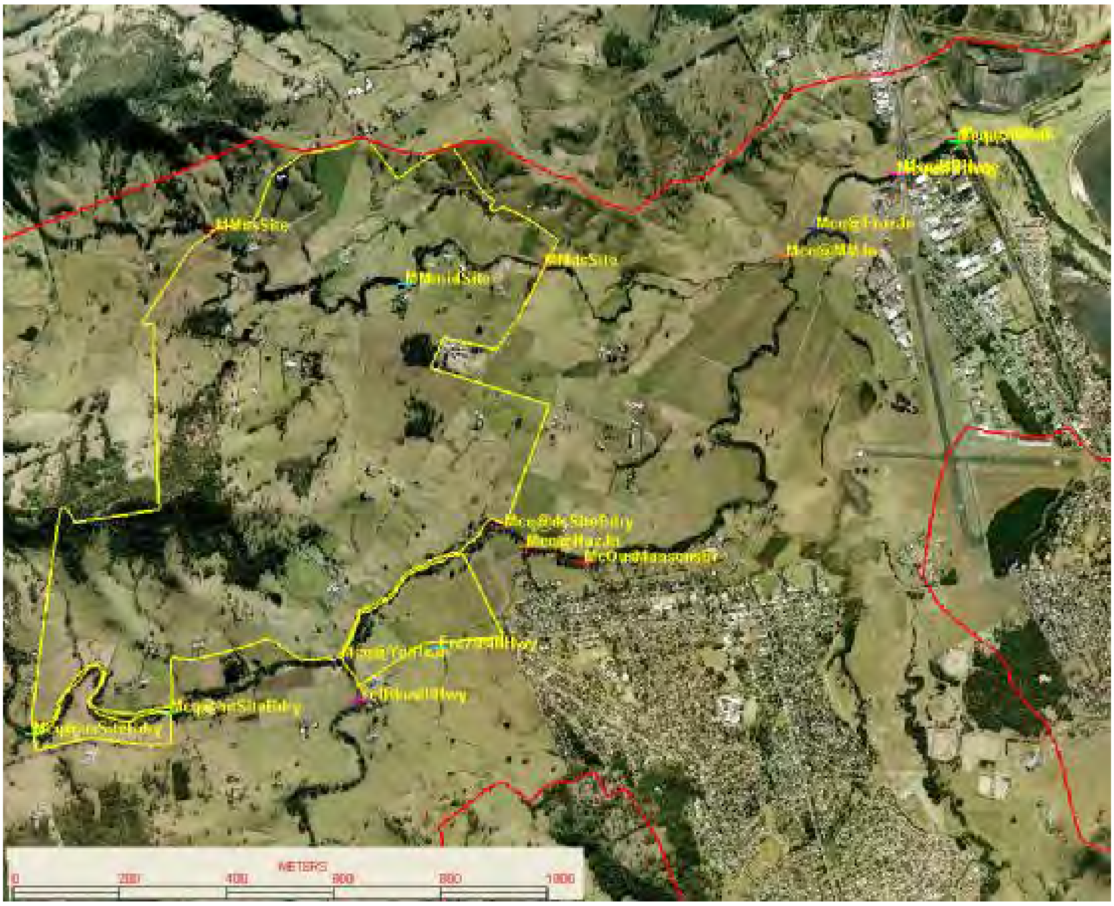


Figure 7.1.4: Selected Design Locations

Table 7.3.3: Design Peak Flood Levels at Selected Locations

Location	**Flood Level (m AHD)**		
	20%AEP	**1%AEP**	**PMF**
Macquarie Rivulet DS of the Illawarra Rail Bridge	3.17	3.98	4.70
Macquarie Rivulet US of the Illawarra Rail Bridge	3.21	4.18	5.49
Macquarie Rivulet DS of the Princes Hwy Rd Bridge	3.84	5.29	6.55
Macquarie Rivulet US of the Princes Hwy Rd Bridge	4.32	5.95	7.82
Macquarie Rivulet @ Frazers Creek Junction	4.93	6.57	8.42
Macquarie Rivulet @ Marshall Mt Creek Junction	4.98	6.61	8.44
Macquarie Rivulet US Mansons Bridge	11.54	12.37	13.06
Macquarie Rivulet @ DS Site Boundary	12.64	12.93	13.52
Macquarie Rivulet @ Hazelton Creek Junction	12.17	12.75	13.43
Macquarie Rivulet @ Yellow Rock Junction	15.95	17.10	17.98
Macquarie Rivulet @ US Site Boundary	23.17	24.52	26.40
Macquarie Rivulet @ Int SiteBdry US Yellow Rock Jcn	19.24	20.94	22.71
Hazelton Ck US Ill Hway	15.03	15.19	15.60
Yellowrock Ck US Ill Hway	16.63	17.66	18.55

Marshall Mt Creek @ DS Site Boundary	7.40	7.79	8.70
Marshall Mt Creek @ Mid Site	10.78	11.80	12.35
Marshall Mt Creek @ US Site Boundary	18.26	18.87	19.29

Note Unless noted otherwise the tabulated US/DS levels are immediately US or DS of the nominated structure, on the centreline of the stream.

Contours of peak flood elevation, flood depth, flood velocity and flood unit flow (V*D), throughout the study area, are reproduced in **Appendices G1 to G12**.

8 FLOOD BEHAVIOUR

8.1 GENERALLY

As evident on the attached graphics, both the Marshall Mount Creek and Macquarie Rivulet valley floors would be substantially inundated by a 1% AEP flood event under existing conditions. While a substantial proportion of the proposed development site is above the level of flooding in such an event, it is largely surrounded by floodwater presenting a problem for access. While a PMF event would more than double peak flows in the two creek systems and substantially increase flood depths, velocities and hazard, it does not greatly increase the plan extents of flooding (the extent of 'flood prone' land) in the vicinity of the proposed development site.

8.2 FLOOD HYDRAULICS

As is apparent in **Appendices G10 G11 and G12**, where the distribution of conveyance (VxD) in the vicinity of the proposed development site is presented, flow patterns are complex, varying substantially from location to location in velocity, depth and direction. Secondary overland floodways are apparent in both valleys that would isolate substantial sections of land as the flood rises, with the potential for this isolated land to ultimately become inundated as the flood continues to rise. While the highest conveyance remains within the banks of each creek, many breakouts and secondary floodways are apparent with VxD levels greater than 3. A particularly pronounced secondary flow path is evident in Marshall Mount Creek at the foot of the spur forming the catchment's northern boundary. A further substantial secondary flow path is apparent in Macquarie Rivulet between the Illawarra Highway and mainstream of Macquarie Rivulet.

In **Appendix G7 G8 and G9** a major diversion out of Macquarie Rivulet onto farmland is evident at Calderwood, upstream of Calderwood Road (Mansons Bridge). This diversion creates a very deep (>3m) and large dynamic storage that in turn flows back in to Macquarie Rivulet downstream of the breakout point or discharges to the east through what appears to be a man made cutting directly onto the combined Marshall Mount/Macquarie Rivulet floodplain.

8.3 FLOOD HAZARD

An assessment of the distribution of provisional hydraulic hazard across the study area is presented in **Appendix G13** (20%AEP), **Appendix G14** (1%AEP) and **Appendix G15** (PMF). These plots reflect the FPDM 2005 provisional hydraulic hazard categories set out in Figure L2 of the manual. The plotted provisional hazard categories are based on the most severe hazard category (from the combination of instantaneous velocity and depth consideration), occurring throughout the event.

As shown in **Appendix G14** (1% AEP), the relatively pronounced ground slopes at the edge of the floodplain in both valleys prevents the development of significant zones of low and/or transitional hazard in most locations. Most of the inundated portions of the site would therefore present a 'high' provisional hydraulic hazard .to those occupying such land. Some areas of low provisional hydraulic hazard are however present in both valleys between the mainstream and secondary floodways and on steeper land on the side slopes of tributary streams, particularly on the southern face of the Marshall Mount valley in the vicinity of the western boundary of the site. It is of note that most older farmhouses are located on land that is <u>not</u> 'flood prone'.

9 ACKNOWLEDGMENTS

This modelling was undertaken by Rienco Consulting at the request of Cardno Forbes Rigby Consulting Engineers to provide background for their review of development options for land in the Macquarie Rivulet catchment.

During compilation of this report, valuable assistance and advice was received from Cardno Forbes Rigby, Shellharbour City Council, The Department of the Environment and Climate Change, Manly Hydraulics Laboratory, AAMHatch Consulting and the Bureau of Meteorology, The assistance of all parties is gratefully acknowledged.

10 REFERENCES

The following documents are cited in this report.

Arcement G & Schneider V. (1984) Guide for Selecting Manning's Coefficients for Natural Channels and Flood Plains,. US Dept Transportation, Federal Highway Administration Report.

Boyd, Rigby & Van Drie (2007) WBNM 2003_V104 – User Manual

Boyd, Sivakumar, Rigby & Downey (1989). A Comparison of Design Flood Estimation Methods. Proceedings Fifth National Local Government Engineering Conference - Sydney.

Boyd, M.J. Rigby, E.H, Sharpin, M.G, Van Drie, R. (1994),. Enhanced Runoff Routing Model WBNM94, Proceedings Water Down Under '94. Adelaide, November 1994

Bowman (1966) Records of the Geological Survey of NSW Vol 14, part 2

Brigham Young University (2007) SMS V9.2 - Surface Water Modelling System - Reference Manual

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

Chow, V.T. (1959). Open Channel Hydraulics. McGraw Hill: New York.

Cordery & Webb (1974). Flood Estimation in Eastern New South Wales - A Design Method. Civil Engineering Transactions, Vol. CE 16, No.1

Davidson (1981). Flooding in Wollongong 1945-1977, A Survey. Occasional Paper No.30, University of N.S.W., Faculty of Military Studies, Dept of Geography.

Forbes Rigby (1996), A Review of Flooding in Macquarie Rivulet Adjacent to Croom Road at Albion Park, NSW, for D Yates - Surveyor.

Forbes Rigby (1995) A Review of Flooding at the Corner of Terry Street and Tongarrra Road, Albion Park, NSW, for Mobil Oil Australia Ltd. .

Forbes Rigby (1994), A Review of Flooding in the Lower Reaches of Macquarie Rivulet and the Impact of Development on Flooding, for Soredo Pty Ltd.

Forbes Rigby (1993), A Review of Flooding in the Lower Reaches of Macquarie Rivulet and the Potential for Cross Flow from Macquarie Rivulet to Albion Creek, for Shellharbour Municipal Council.

Forbes Rigby (1991), A Supplementary Report on the Impact of Development on Land adjacent to Macquarie Rivulet on Flooding in Macquarie Rivulet, for Soredo Pty Ltd

Forbes Rigby (1990), A Report on the Impact of Flooding on the Development of Land adjacent to Macquarie Rivulet, Yallah, for Soredo Pty Ltd

Foreman I & Rigby E (1990) Urban Flooding & Flood Mitigation in the Northern Illawarra Region, Proceedings 30th Annual Flood Mitigation Conference, Wollongong, May 1990.

Hazelton, P.A. (1992). Soil landscapes of the Kiama 1:100 000 sheet, Department of Conservation and Land Management, Sydney

Fuller & Mills (1985) Native Trees of Central Illawarra

Hicks D & Mason P (1991) Roughness Characteristics of New Zealand Rivers, Water Resources Survey DSIR Marine and Freshwater, Kilbirnie Wellington, New Zealand.

IEAust (1987). Australian Rainfall and Runoff - A Guide to Flood Estimation, Volumes 1 & 2.

Kinhill Engineers (1995), Extension to Albion Park Flood Study, Final Report for Shellharbour Municipal Council, Kinhill Engineers Reference SE 2158 dated June 1995

Lawson & Treloar (1993), Lake Illawarra Entrance Improvement Hydraulic Numerical Modelling, Report prepared for Public Works Department - NSW

Neller, Ronald J (1976), Morphology of an osage stream: the meanders of the Macquarie Rivulet, University of Wollongong, NSW

New South Wales Government (2005). Floodplain Development Manual.

Public Works (1991). Flooding of the Wollongong area - 6th to 12th June 1991.

Rienco Consulting (2007) Flood Modelling Report – Hyundi Motor Dealership Princes Highway Albion Park Rail, Report prepared for Jordan Mealey Consulting Engineers, October 2007, Ref 7016-1

Rienco Consulting (2007) Flood Modelling Report – Land Adjacent to Albion Park Airport (Existing Conditions), Report prepared for Jordan Mealey Consulting Engineers, February 2007, Ref 7001-1

Rienco Consulting (2007) Flood Modelling Report – Land Adjacent to Albion Park Airport (Post Development Conditions), Report prepared for Jordan Mealey Consulting Engineers February 2007, Ref 7001-1

Rigby E.H, Roso S. (2006), The Impact of an Embedded Design Storm on Flows within a Catchment, Proceedings IEAust. 30th Hydrology and Water Resources Symposium, 2006, Wollongong.

Rigby E.H, Boyd M.J, Roso S, Van Drie R (2003), Storms, Storm Bursts and Flood Estimation A Need for Review of the AR&R Procedures, Proceedings IEAust. 28th Hydrology and Water Resources Symposium, 2003, Wollongong.

Rigby E. H, Silveri P (2001) The Impact of Blockages on Flood Behaviour in the Wollongong Storm of August 1998 Proc 6th Conference on Hydraulics in Civil Engineering. November 2001, Hobart.

Rigby E.H, Bannigan D (1996), The Embedded Design Storm Concept – A Critical Review, Proceedings IEAust. 23rd Hydrology and Water Resources Symposium, 1996, Hobart.

Rigby E (1993), Modelling Flood Flows in Macquarie Rivulet using FESWMS-2DH, International Conference on Environmental Management Geowater and Engineering Aspects, University of Wollongong February 1993.

BMT WBM (W Symes Ed) (2009), Tuflow User Manual – Gis based hydrodynamic modelling

Roso S, Boyd M and Chisolm L (2006) Assessment of Spatial Analysis Techniques for Estimating Impervious Cover. Proc 30th Hydrology and Water Resources Symposium, Launceston Tasmania December 2006.

Shellharbour City Council (2004), DCP 04/1 - Flood Risk Management", Shellharbour City Council, Shellharbour NSW.

University of Wollongong (1976), Illawarra Lake: an environmental assessment project carried out on behalf of the Council of the City of Wollongong, Wollongong City Council and University of Wollongong, Wollongong NSW.

Wargon Chapman (1980) Report on Investigation for New Railway Underbridge over Macquarie Rivulet at Albion Par 101.169 km (Illawarra Line), for the State Rail, Wargon Chapman & Associates Pty Ltd Reference : 195073 dated 17 October,1980.

WRF (E Rigby Ed)(1996) Development of Macquarie Rivulet as a Reference Catchment for the Illawarra,,Report prepared for the Water Research Foundation by the Illawarra Regional Sub-committee of the Water Research Foundation, December 1996.

Water Resources Commission (1986) Albion Park Flood Study, Report dated January 1986.

APPENDICES

A. THE CATCHMENT

A.1 Location Plan
A.2 Topography
A.3 Geology
A.4 Soils
A.5 Cover & Landuse
A.6 Stream Network
A.7 Gauging

B. SUPPORTING DATA

B.1 Aerial Photography
B.2 ALS Survey Data
B.3 Stream Photography
B.4 Structure Survey & Photography
B.5 June 1991 Rainfall Hyetographs
B.6 June 1991 Sunnybank Stage Record
B.7 June 1991 Princes Highway Stage Record
B.8 Sunnybank Rating Curves
B.9 Princes Highway Rating Curves
B.10 June 1991 Flood Photography
B.11 June 1991Recorded Flood Levels

C. HYDROLOGIC MODEL ESTABLISHMENT

C.1 Model Layout
C.2 Model Impervious Cover
C.3 Model Storages & Diversions

D. HYDRODYNAMIC MODEL ESTABLISHMENT

D.1 Model Plan Extents
D.2 Model Topography
D.3 ModelSurface Roughness
D.4 Model Structures
D.5 Model Boundary Conditions

E. MODEL CALIBRATION

E.1 Recorded –v- Modelled June 91 Hydrograph at PH Gauge
E.2 Recorded –v- Modelled June 91 Hydrograph at SB Gauge
E.3 Recorded –v- Modelled June 91 Peak Flood Surface
E.4 Adopted Hydrologic Parameters
E.5 Adopted Surface Roughness Values

F. DESIGN FLOOD HYDROLOGY

F.1 Hydrographs at Locations of Interest - 1%AEP Event
F.2 Hydrographs at Locations of Interest - PMF Event

G. DESIGN FLOOD HYDRAULICS

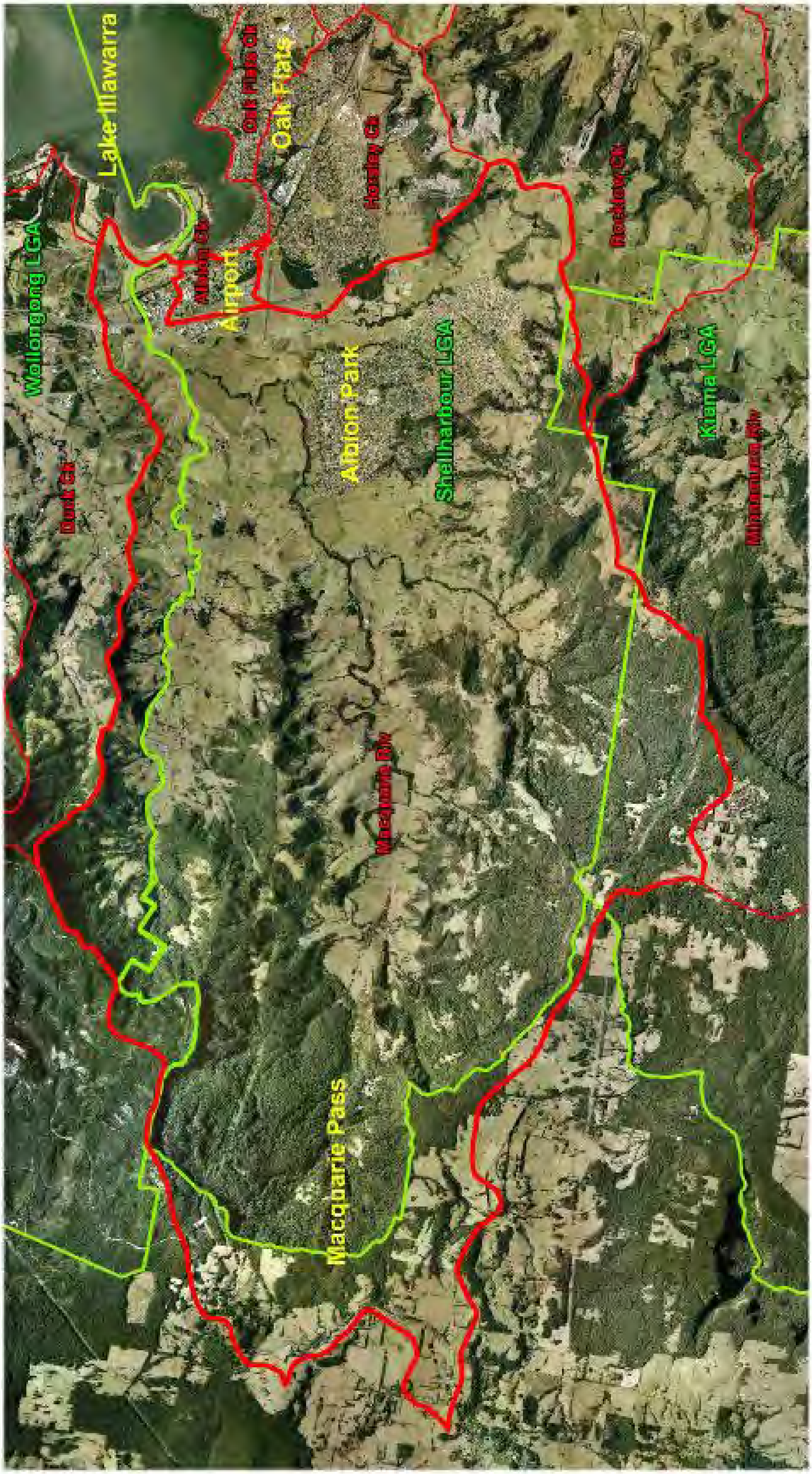
G.1 20% AEP Peak Elevation Flood Surface
G.2 1% AEP Peak Elevation Flood Surface
G.3 PMF Peak Elevation Flood Surface
G.4 20% AEP Peak Velocity Flood Surface
G.5 1% AEP Peak Velocity Flood Surface
G.6 PMF Peak Velocity Flood Surface
G.7 20% AEP Peak Depth Flood Surface
G.8 1% AEP Peak Depth Flood Surface
G.9 PMF Peak Depth Flood Surface
G.10 20% AEP Peak VxD Flood Surface
G.11 1% AEP Peak VxD Flood Surface
G.12 PMF Peak VxD Flood Surface
G.13 20% AEP Prov Hyd Hazard Flood Surface
G.14 1% AEP Prov Hyd Hazard Flood Surface
G.15 PMF Prov Hyd Hazard Flood Surface

THE CATCHMENT

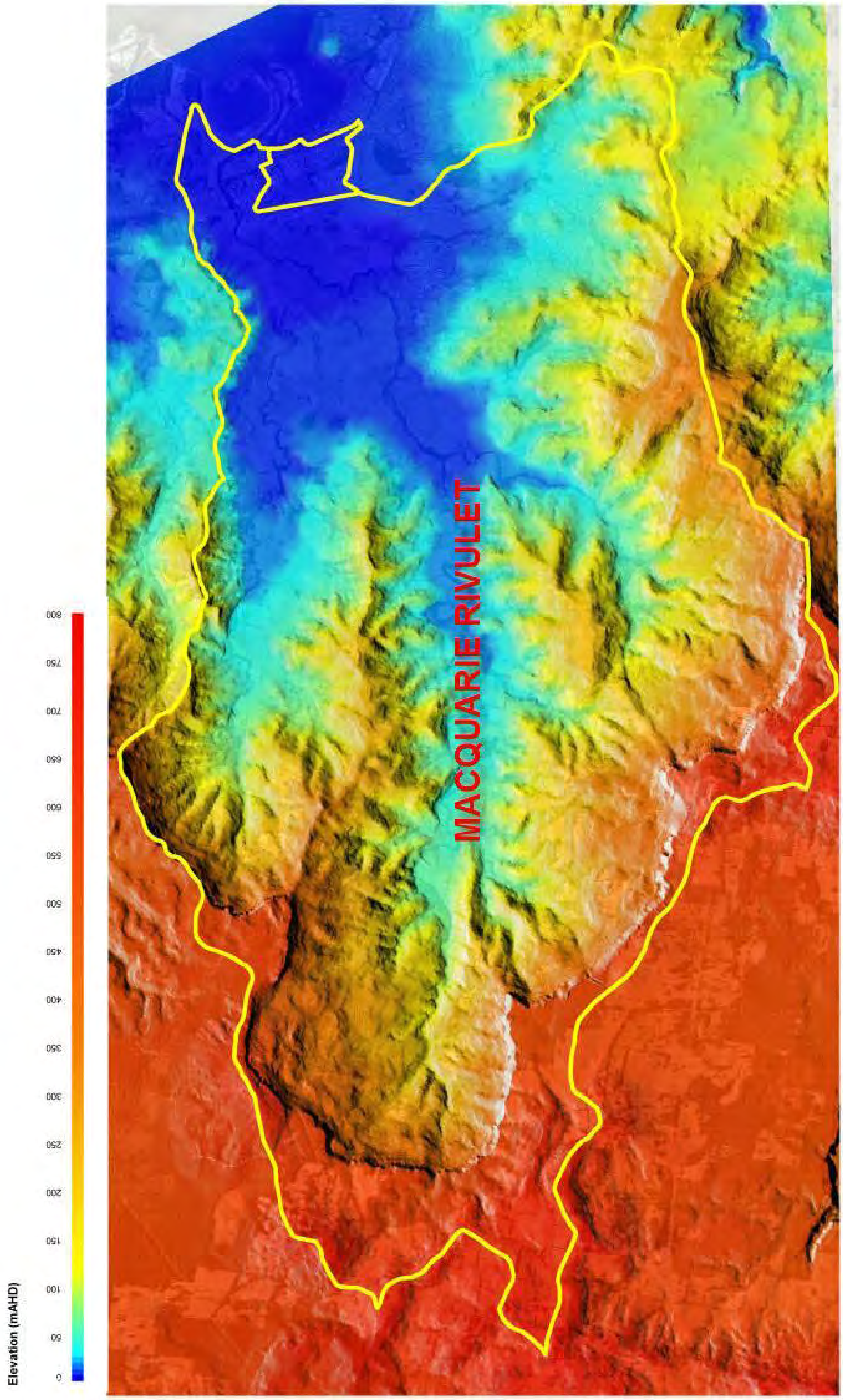
A.1 **Location**
A.2 **Topography**
A.3 **Geology**
A.4 **Soil Types**
A.5 **Cover & Landuse**
A.6 **Stream Network**
A.7 **Gauging**

A
A
A
A

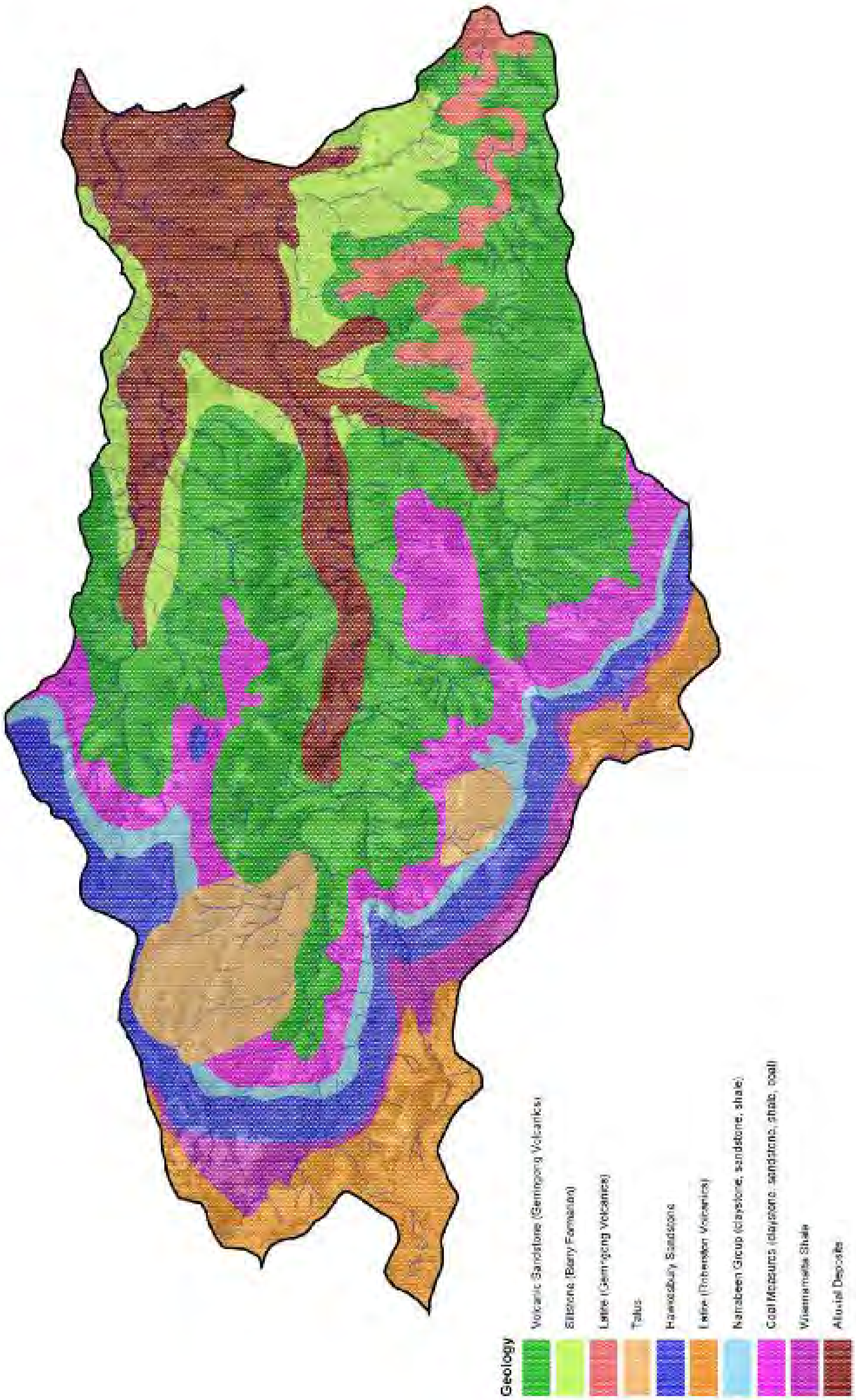
APPENDIX A



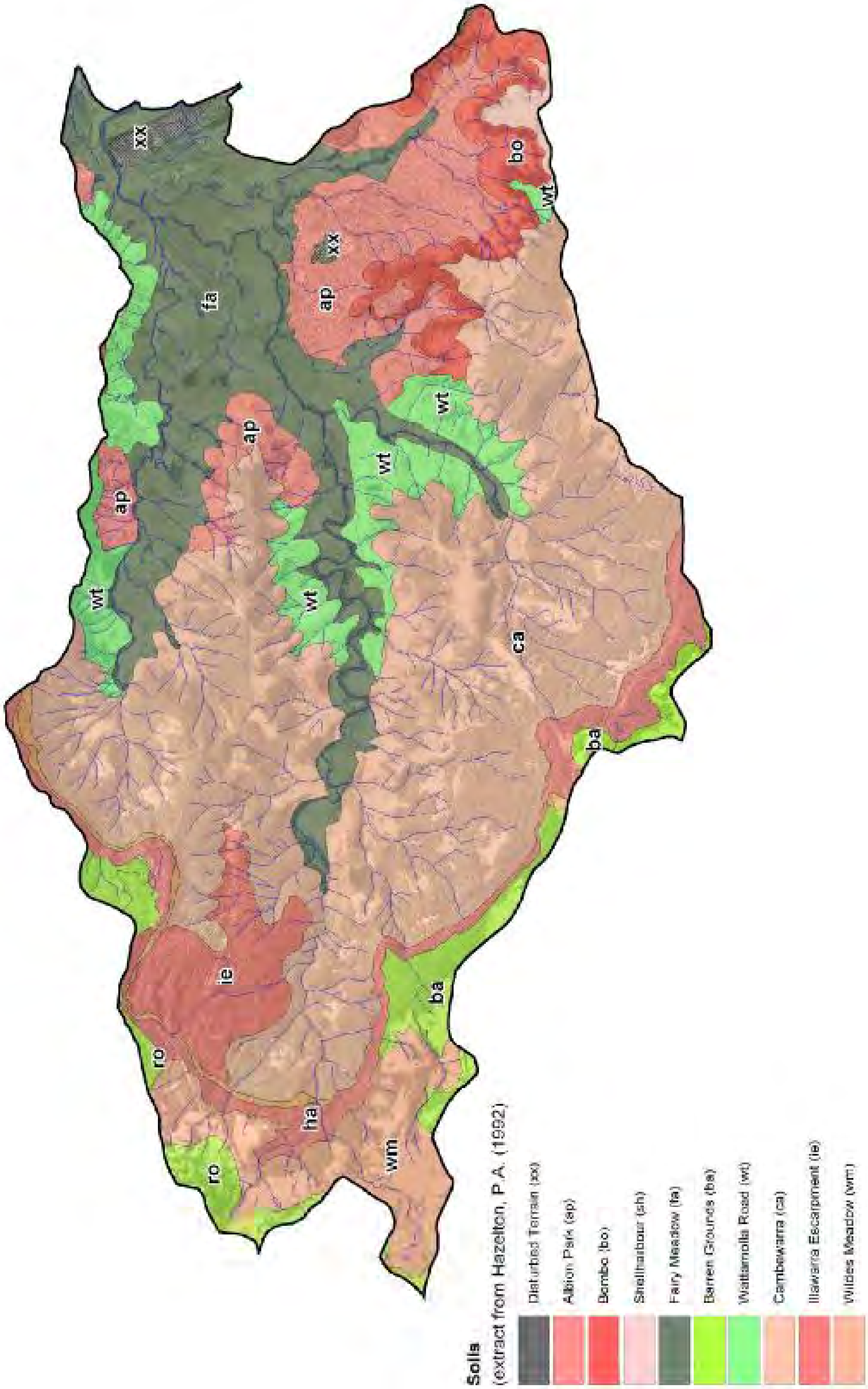
APPENDIX A1. CATCHMENT LOCATION



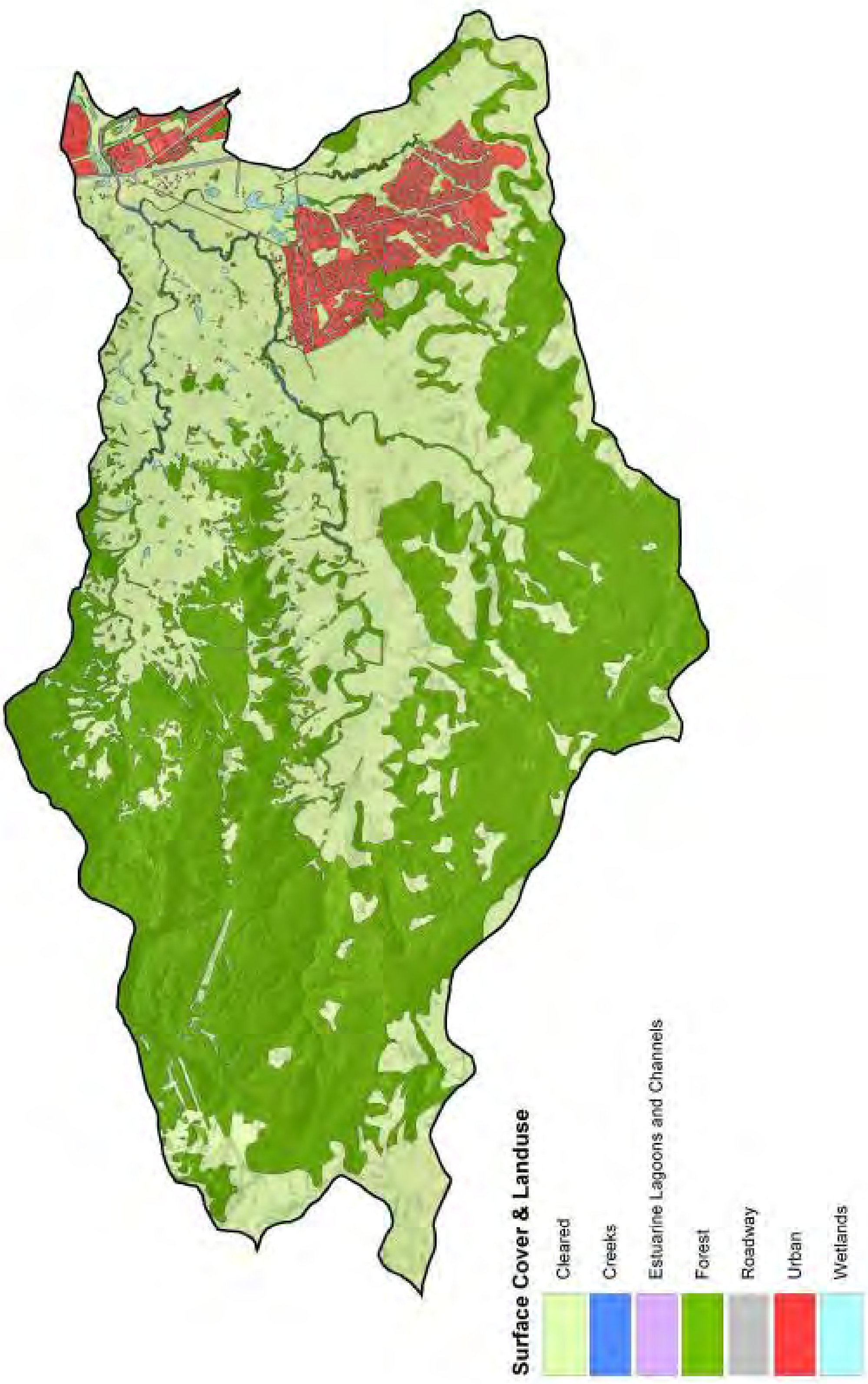
APPENDIX A2. CATCHMENT TOPOGRAPHY



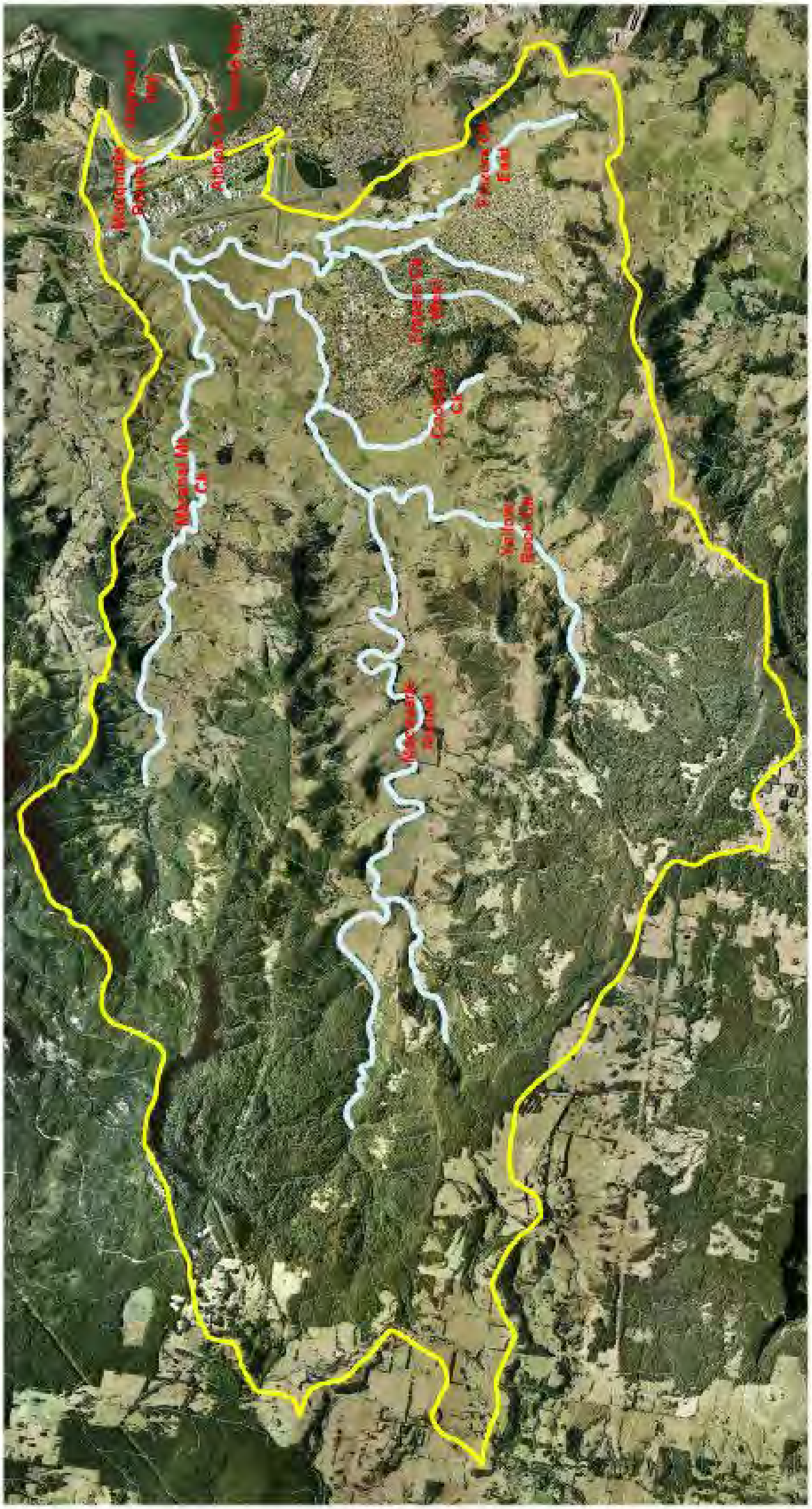
APPENDIX A3. CATCHMENT GEOLOGY



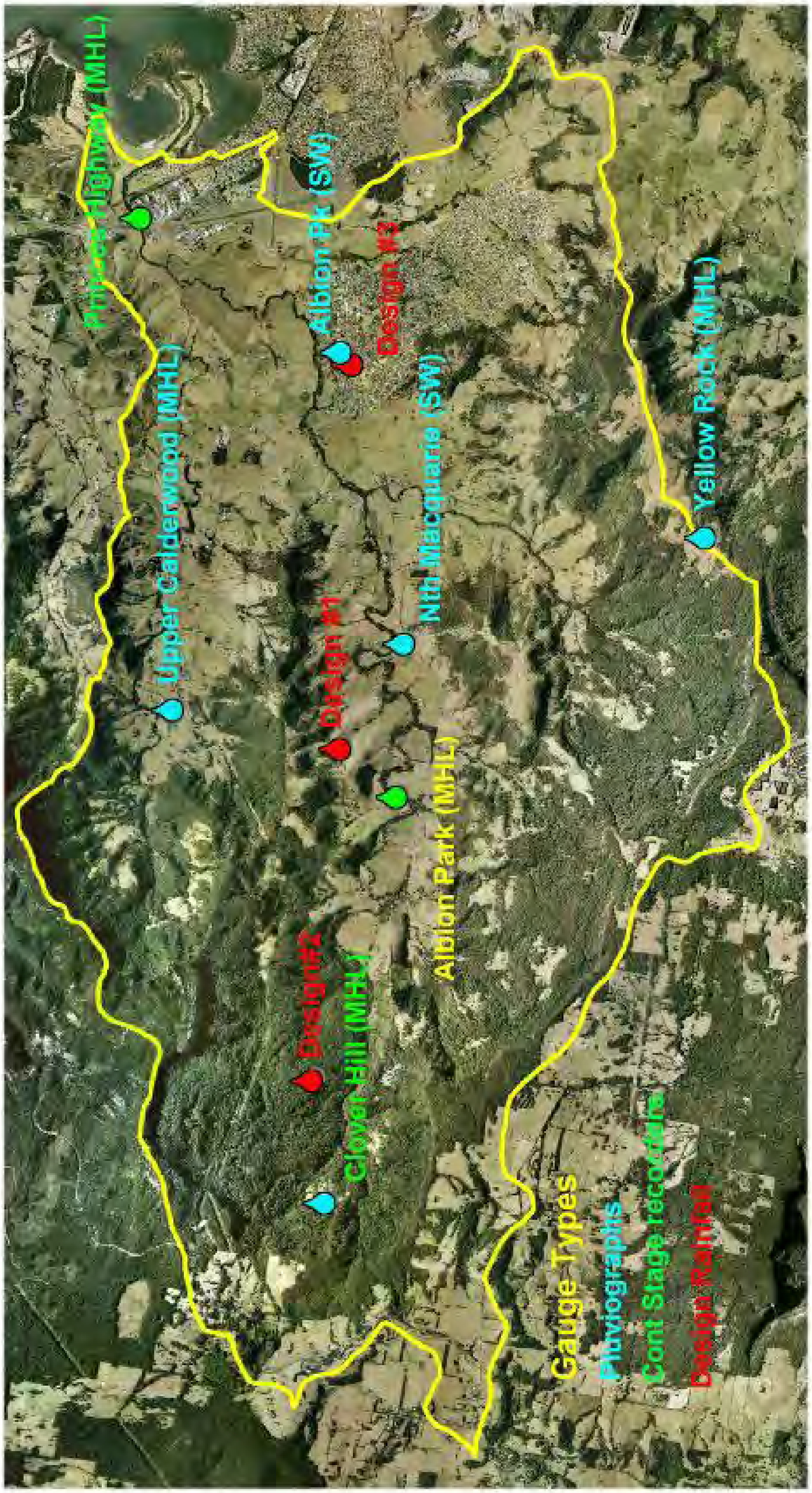
APPENDIX A4. CATCHMENT SOIL TYPES



APPENDIX A5. CATCHMENT COVER & LANDUSE (2005)



APPENDIX A6. CATCHMENT STREAM NETWORK



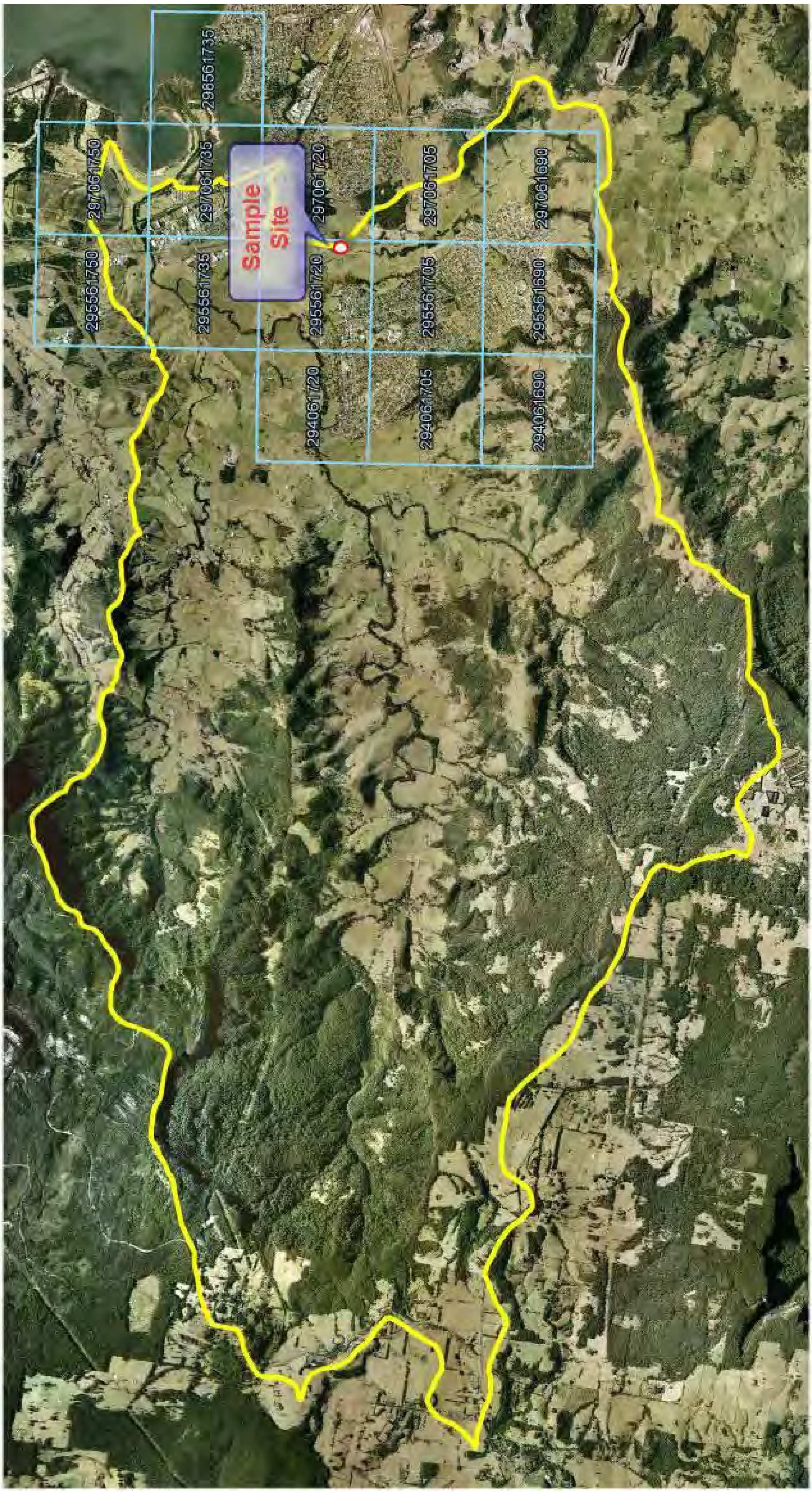
APPENDIX A7. CATCHMENT GAUGES

SUPPORTING DATA

B.1 **Aerial Photography**
B.2 **ALS Survey Data**
B.3 **Stream Photography**
B.4 **Structure Survey & Photography**
B.5 **June 1991 Rainfall Hyetographs**
B.6 **June 1991 Albion Park Stage Record**
B.7 **June 1991 Princes Highway Stage Record**
B.8 **Albion Park(Sunnybank) Rating Curve**
B.9 **Princes Highway Rating Curve**
B.10 **June 1991 Flood Photography**
B.11 **June 1991Recorded Flood Levels**

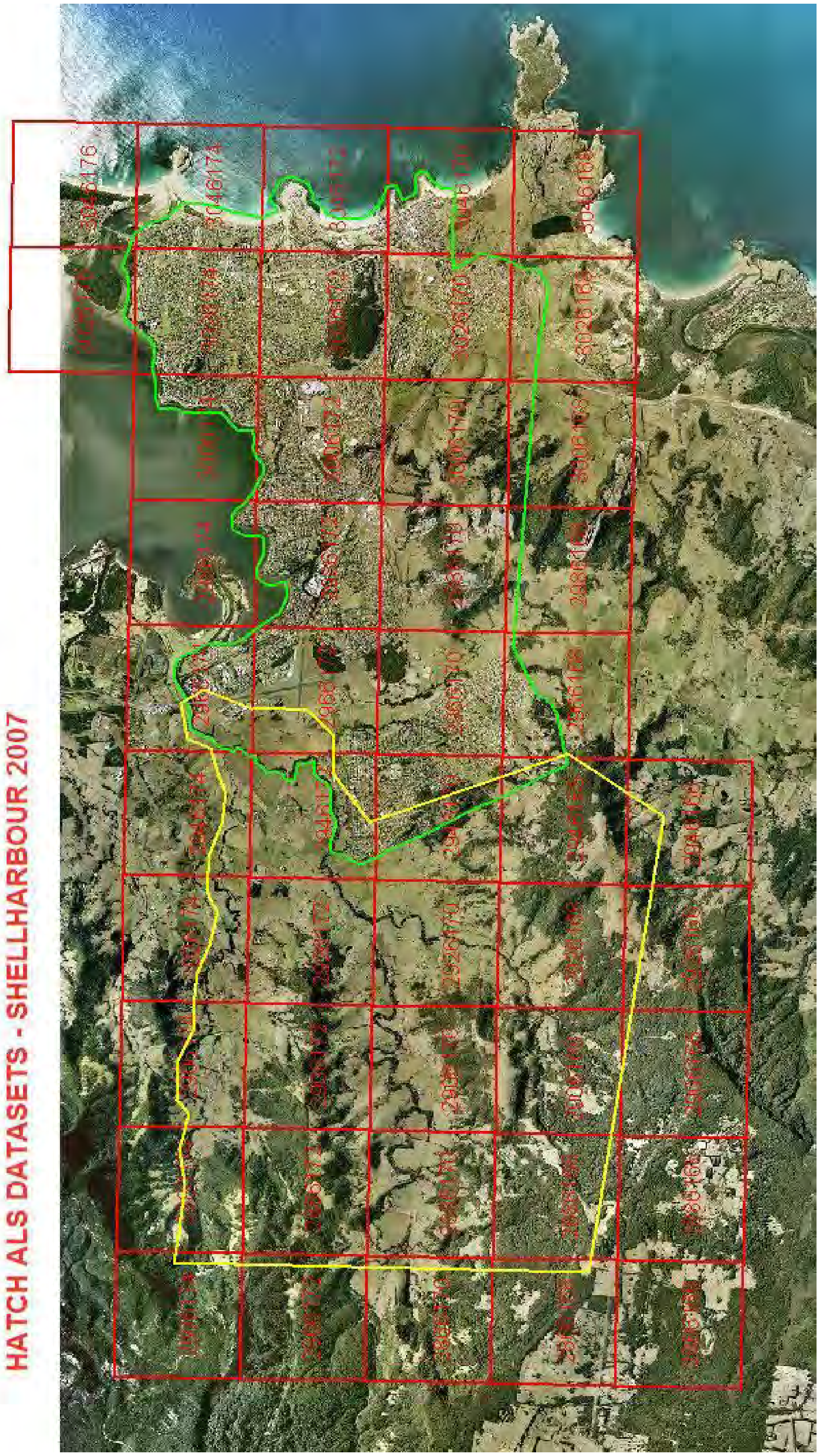
B
B
B
B

APPENDIX B



APPENDIX B1.1. AERIAL PHOTOGRAPHY – COVERAGE

APPENDIX B1.2. AERIAL PHOTOGRAPHY - SAMPLE



APPENDIX B2. ALS SURVEY DATA

Macquarie Rivulet D/S Illawarra Rail Bridge (Feb 2007)

Macquarie Rivulet D/S Princes Highway Road Bridge (Feb 2007)

APPENDIX B3. STREAM PHOTOGRAPHY

Frazers Creek D/S Illawarra Highway (Feb 2007)

Town Creek D/S Illawarra Highway (Feb 2007)

APPENDIX B3. STREAM PHOTOGRAPHY (ctd)

Frazers Creek West D/S Tongarra Rd (Feb 2007)

Frazers Creek Central D/S Tongarra Rd (Feb 2007)

APPENDIX B3. STREAM PHOTOGRAPHY (ctd)

Frazers Creek East D/S Tongarra Rd (Feb 2007)

APPENDIX B3. STREAM PHOTOGRAPHY (ctd)

Albion Creek D/S Princes Highway (Feb 2007)

Albion Creek D/S Shearwater Drive (Feb 2007)

APPENDIX B3. STREAM PHOTOGRAPHY

ID	Location	Structure	Dimensions	U/S Inv (m)	D/S Inv (m)	L (m)	'n'
14	Albion Creek @Shearwater Dr	Single Bebo Arch	1 * 10mW * 3mH	0.5	0.5	20	0.012
15	Albion Creek @ Illawarra Rail	Multi Barrel Pipe Culvert	5 * 2.6m Dia Rail over at RL 5.1m AHD	-0.35	-0.35	30	0.012
16	Albion Creek @ Princes Hway	Multi Cell Box Culvert	<1.5m diag(not inc)				
1	Macquarie Riv @ Illawarra Rail	Multi Span Conc Bridge	17 * 7.6m Spans RL 4.54m Obvert RL 5.64m Top of rail	Vble	Vble	6	-0.030
2	Macquarie Rivulet @ Princes Hway	Twin Multi Span Conc Bridge	5 * 22m Spans RL 6.35 Obvert RL 8.07 Top of Kerb	Vble	Vble	25	-0.030
3	Wollongurry Creek @ Illawarra Rail	Multi Cell Box Culvert	2 * 2.7mW * 2.7mH RL5.8 Top of Rail	0.91	0.81	28	0.012
4	Wollongurry Creek @ Princes Hway	Multi Barrel Pipe	3 * 1.75m Dia Road over at RL8.5	1.83	1.41	81	0.012

		Culvert					
5	Frazers Creek @ Illawarra Hway	Multi Barrel Pipe Culvert	4 * 1.05m Dia Road over at RL 2.85	1.4	1.4	15	0.012
8	Frazers Creek @ Tongarra(west)	Multi Cell Box Culvert	4 * 2.5mW * 1.55mH Road over at RL 6.58	4.54	4.64	16	0.012
7	Frazers Creek @ Tongarra(central)	Single Cell Box Culvert	1 * 2.4mW * 1.25mH Road over at RL 6.58	4.75	4.68	16	0.012
6	Frazers Creek @ Tongarra(east)	Single Span Conc Bridge	8.1m Span RL 9.17m Obvert Road over at RL10.13	Vble	Vble	16	0.030
9	Town Creek @ Illawarra Hway	Multi barrel Pipe Culvert	3 * 0.9m Dia Road over at RL 6.0	4.5	4.5	15	0.012
11	Cooback Creek @Illawarra Hway	Multi Cell Box Culvert	4* 2.4W * 1.2H Road over at RL 14.85	13.00	13.00	20	0.012
12	Yellowrock Creek @Illawarra Highway	Multi Span Conc Bridge	6.5/10.0/5.2m spans Road over at RL17.00	12.5	12.5	16	0.050
10	Macquarie Rivulet @Calderwood Rd (Mansons Bridge)	Multi Span Steel/Conc Bridge	6 * 7m spans Road over at RL 10.6	5.0	5.0	16	0.050
13	Marshall Mt Creek @ Marshall Mt Rd	2 Span Conc Bridge	2 * 9m spans Road over at RL 18.00	16.0	16.0	16	0.050

SUMMARY OF STRUCTURES INCORPORATED INTO HYDRAULIC MODEL

APPENDIX B4. STRUCTURE SURVEY

Original Illawarra Rail Bridge over Macquarie Rivulet circa 1908

Present Illawarra Rail Bridge Rail Bridge over Macquarie Rivulet

APPENDIX B4. STRUCTURE PHOTOGRAPHY

Early Princes Highway Road Bridge over Macquarie Rivulet circa 1950

Present Macquarie Rivulet Road Bridge over Macquarie Rivulet

APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)

Weir in Macquarie Rivulet near Meadow View

Illawarra Highway Road Culvert @ Frazers Ck

APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)

Illawarra Highway Culvert @ Town Creek

Tongarra Rd Culvert @ Frazers Ck (West)

APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)

Tongarra Rd Culvert @ Frazers Ck (Central)

Tongarra Rd Bridge @ Frazers Ck (East)

APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)

Albion Ck Culvert @ Princes Highway

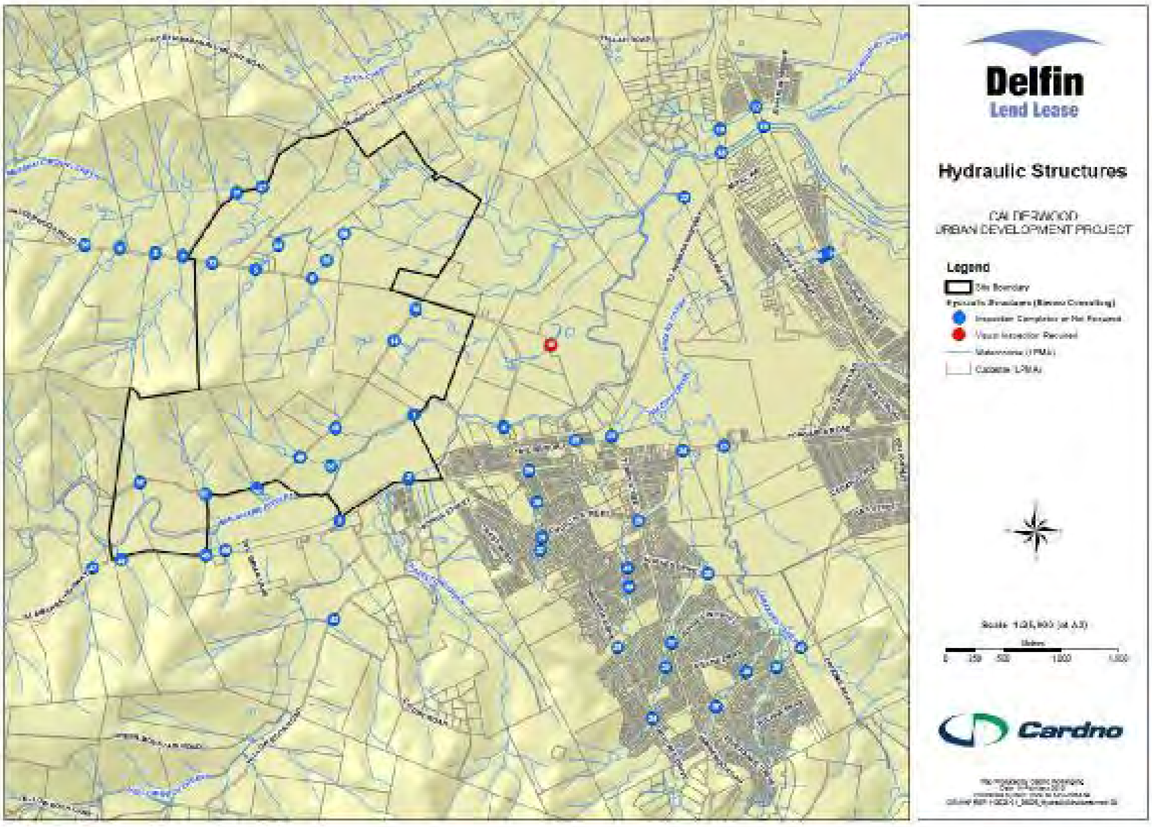
Albion Ck Culvert @ Illawarra Rail

APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)

Albion Ck Culvert @ Shearwater Dr

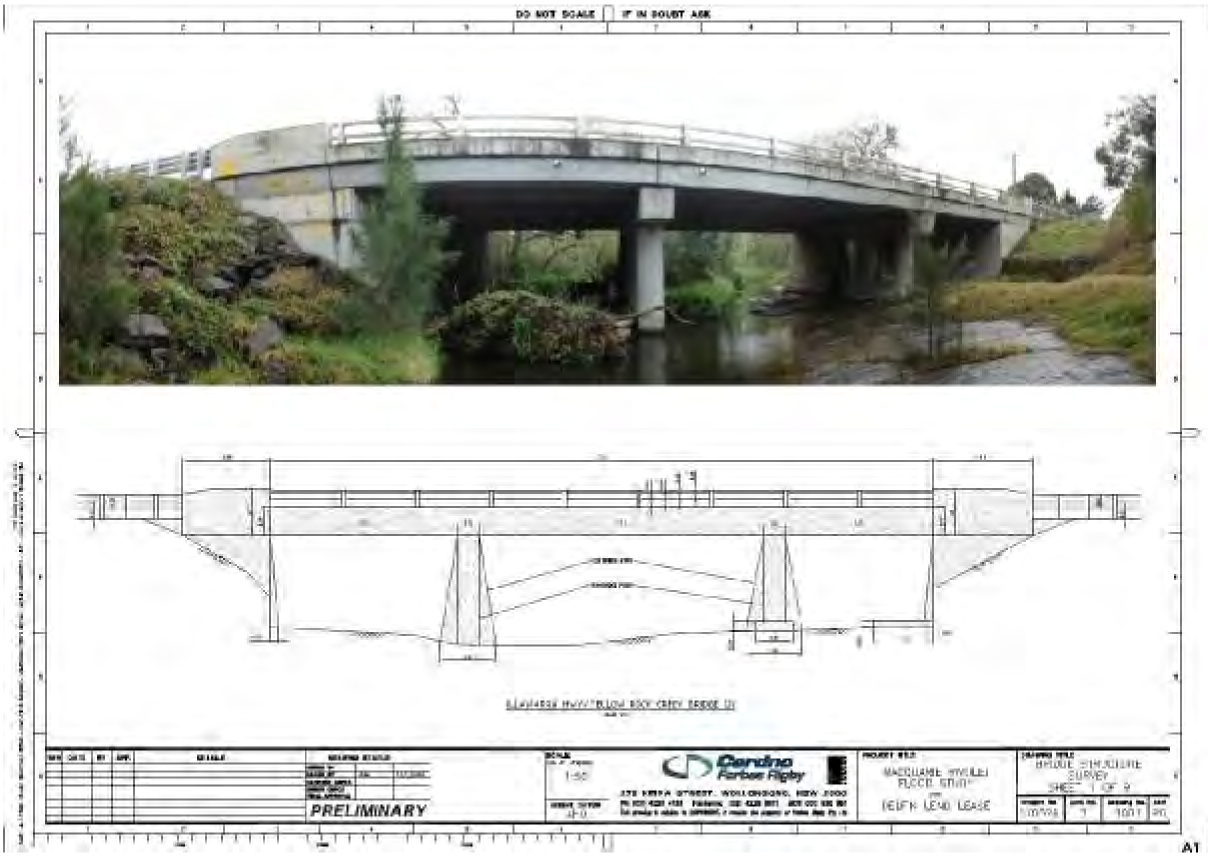
APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)

In 2009, at the commencement of this study, Cardno Forbes Rigby inspected, surveyed and took photographs of each of the various hydraulic structures present in or close to the proposed development site. These structures are documented on the following drawings.

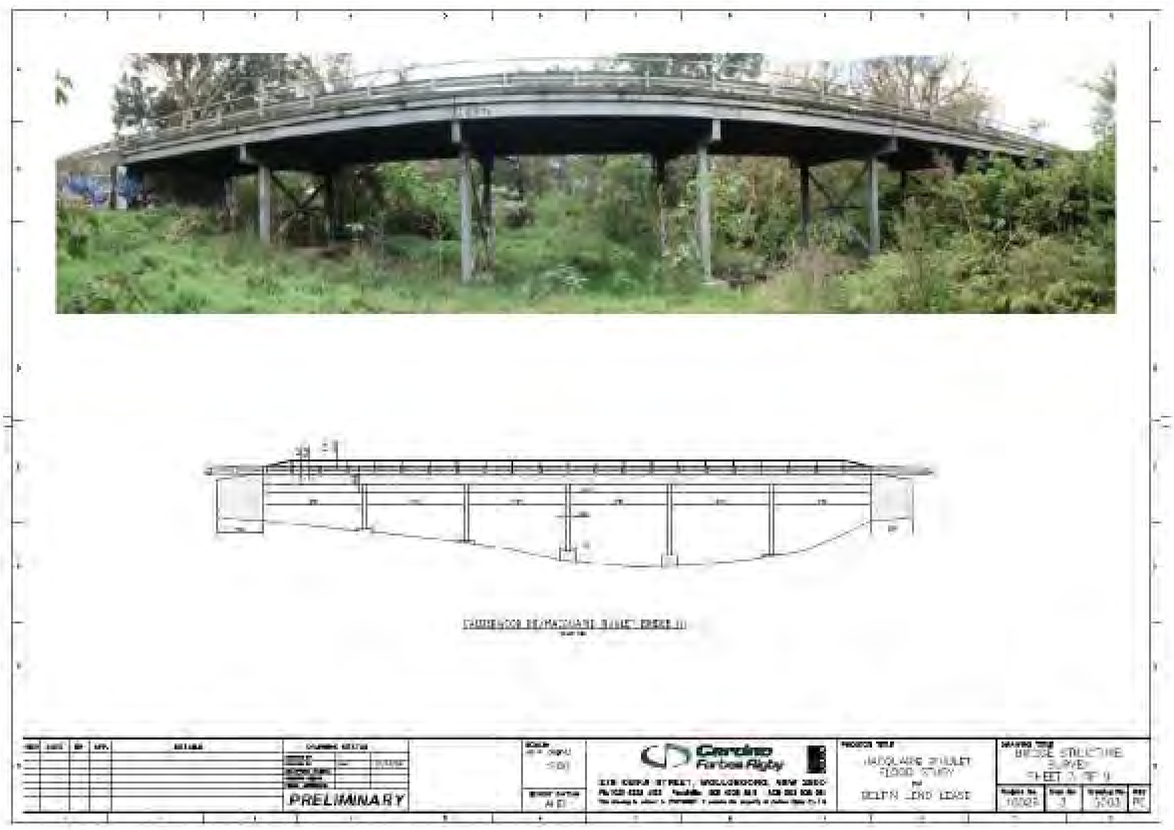


STRUCTURE SURVEY 2009 - LOCATION PLAN

APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)

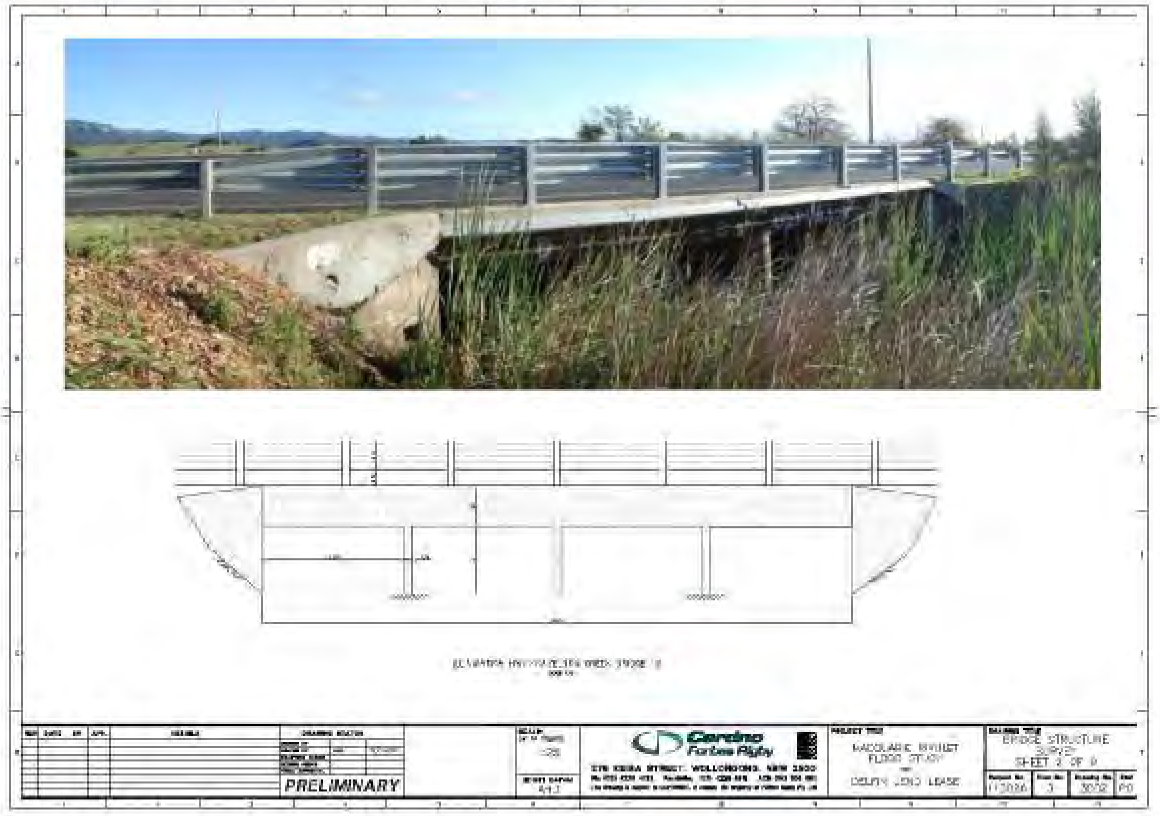


BRIDGE OVER YELLOW ROCK CK – ILLAWARRA HWAY



MANSONS BRIDGE – CALDERWOOD RD

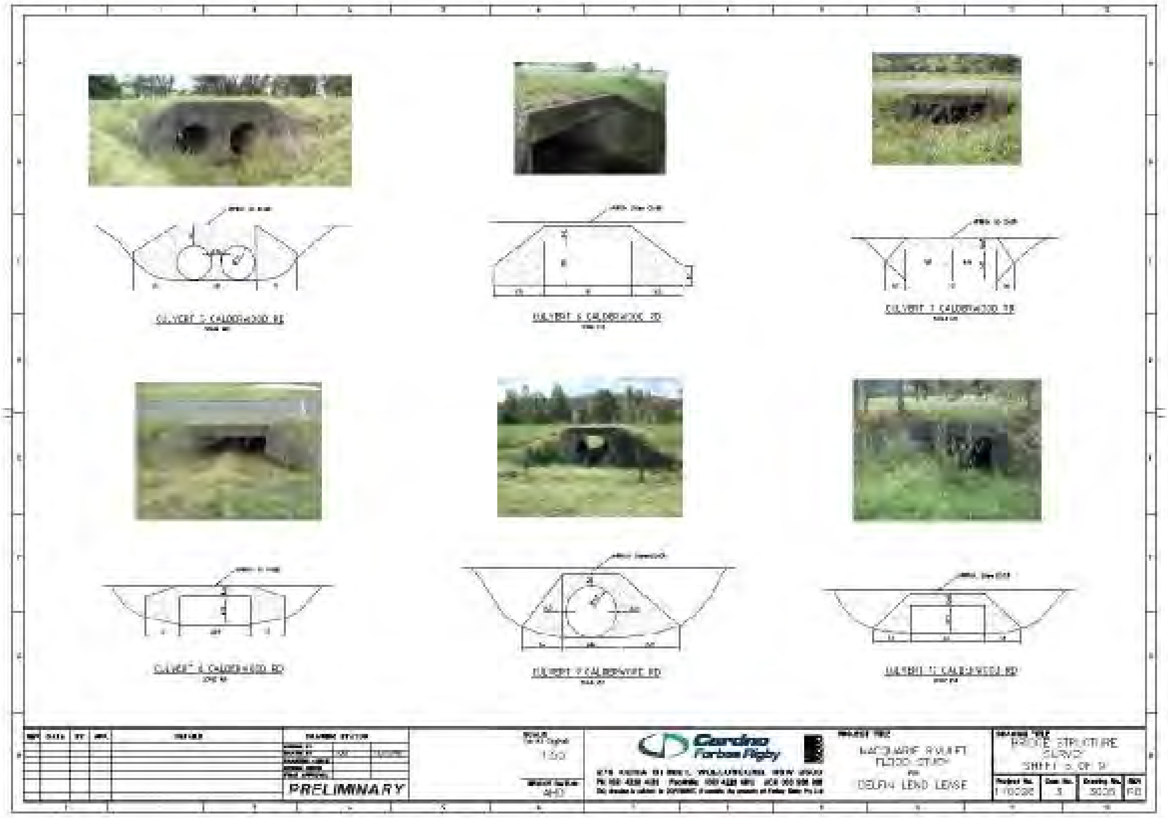
APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)

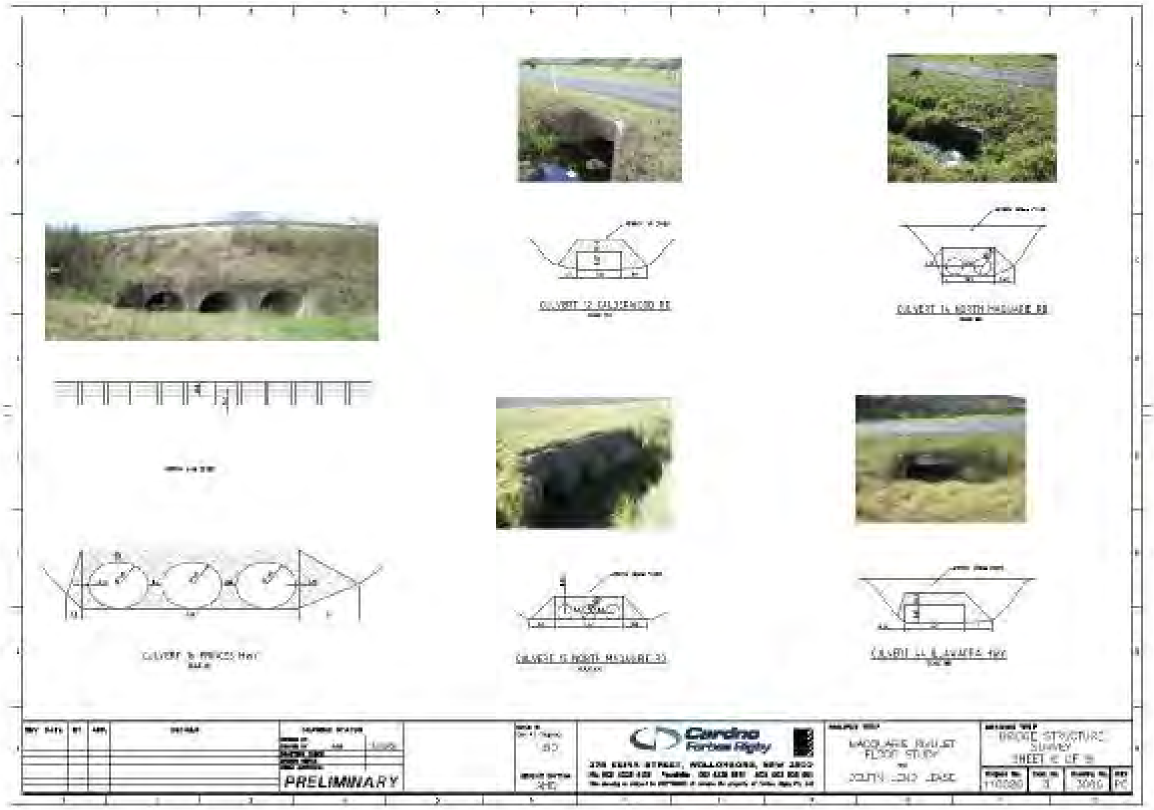


BRIDGE OVER HAZELTON CK – ILLAWARRA HWAY

BRIDGE OVER MARSHALL MT CK – MARSHALL MT RD

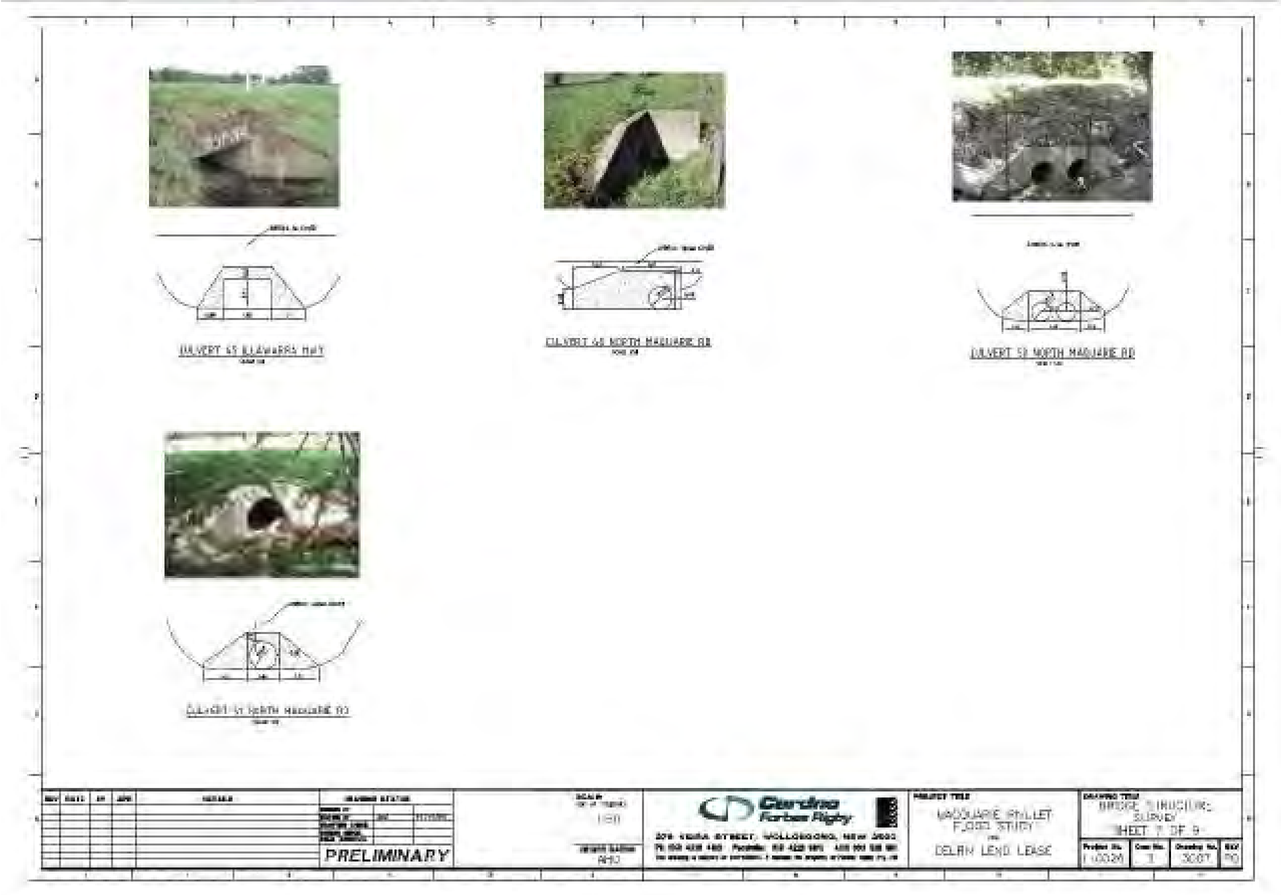
APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)





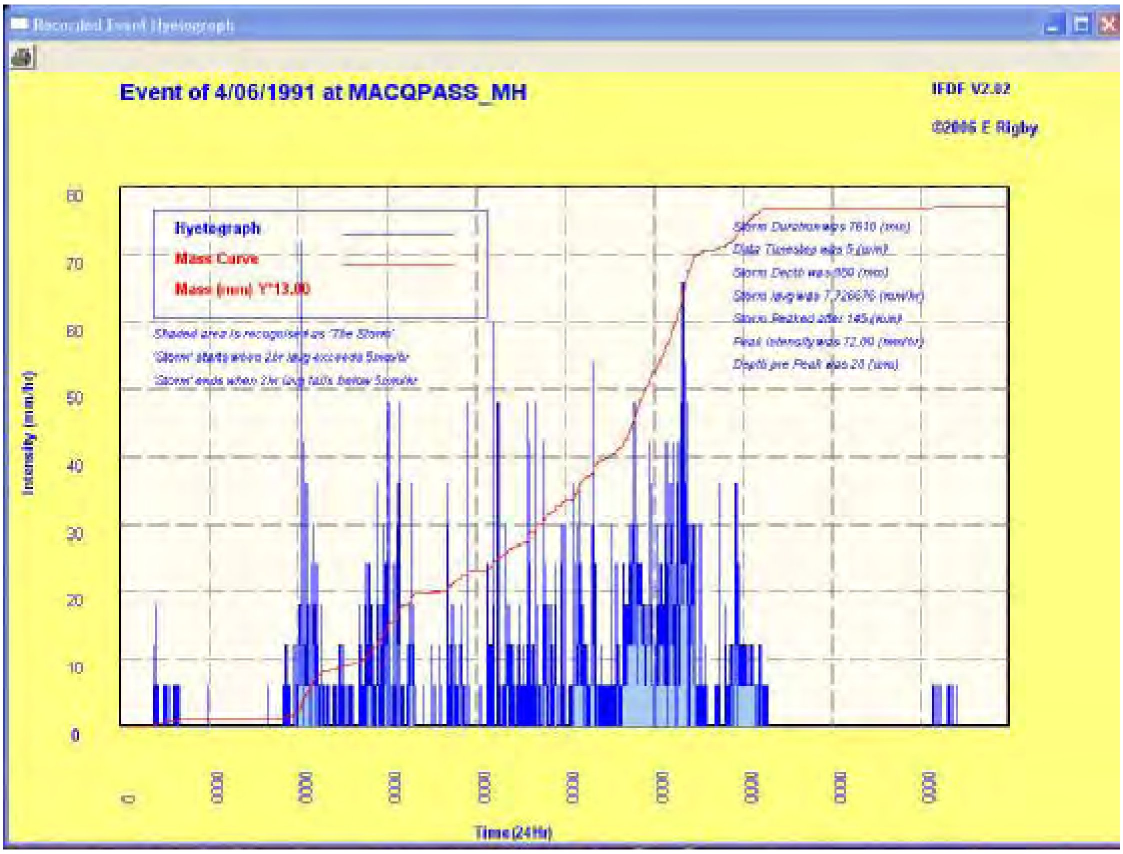
CULVERTS IN OR NEAR TO SITE

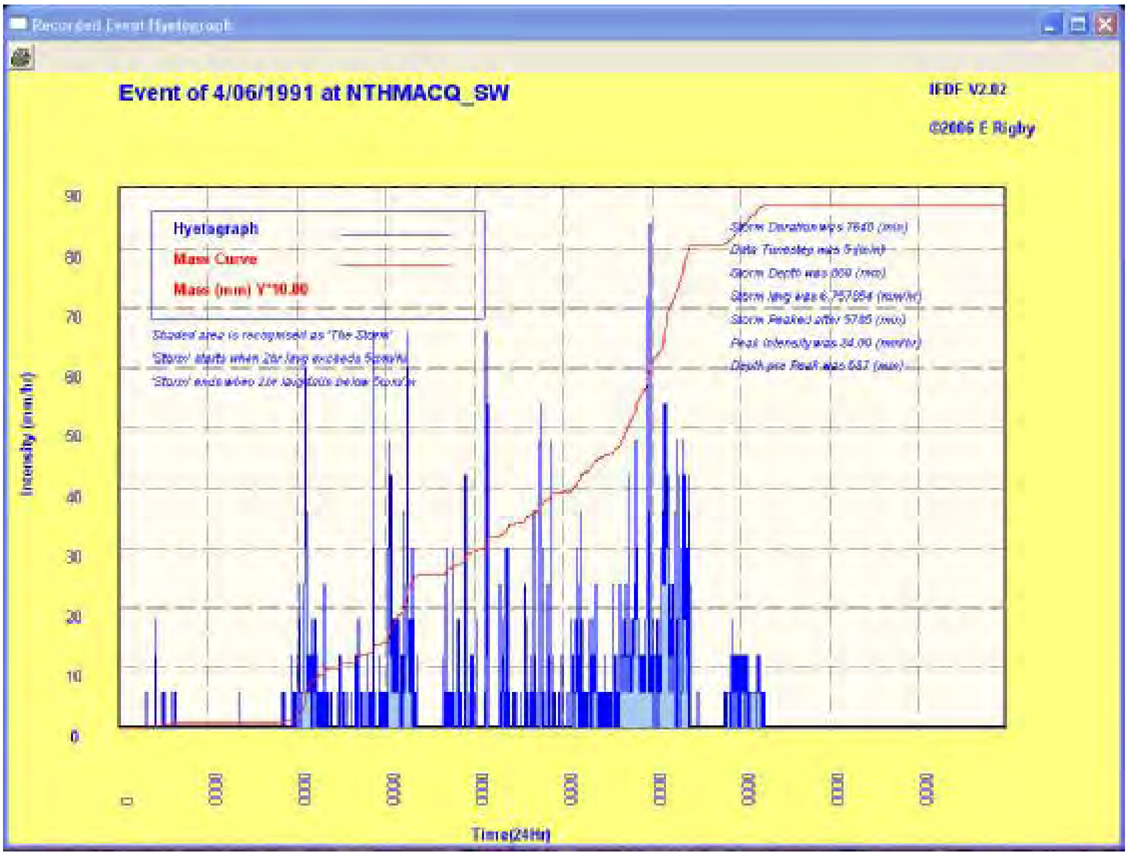
APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)



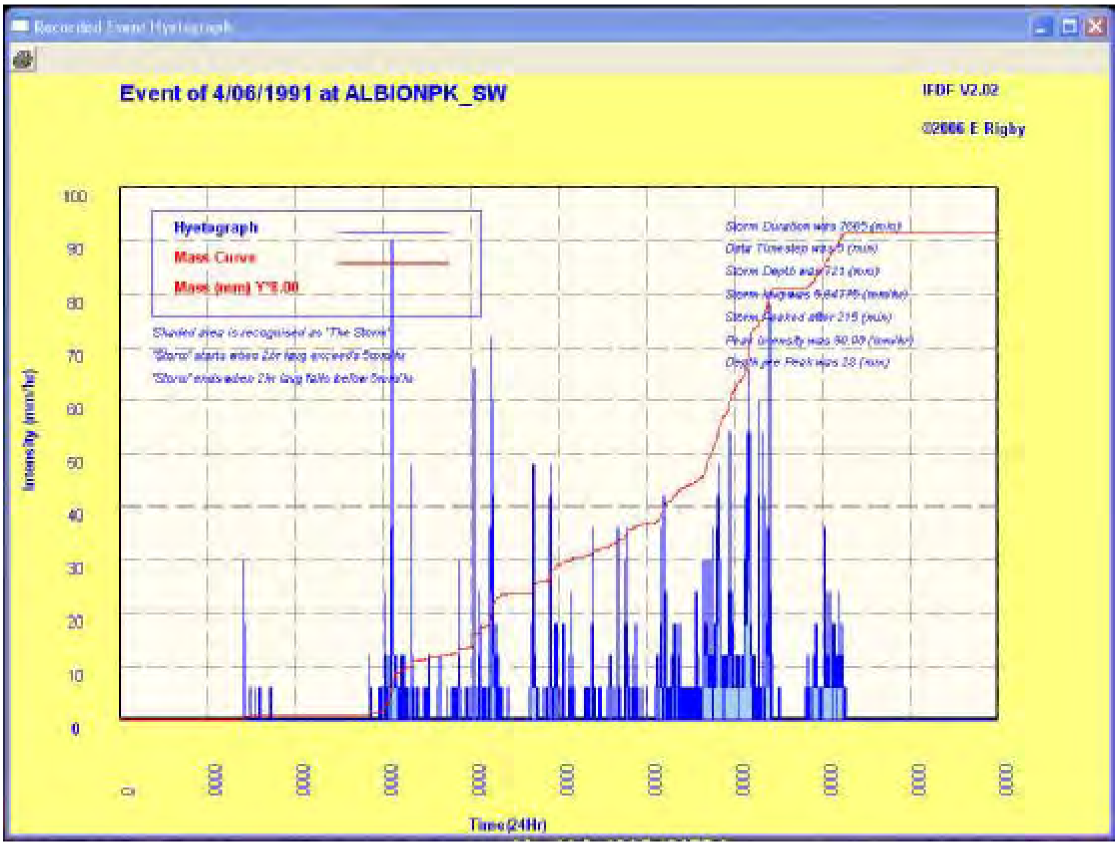
CULVERTS IN OR NEAR TO SITE (ctd)

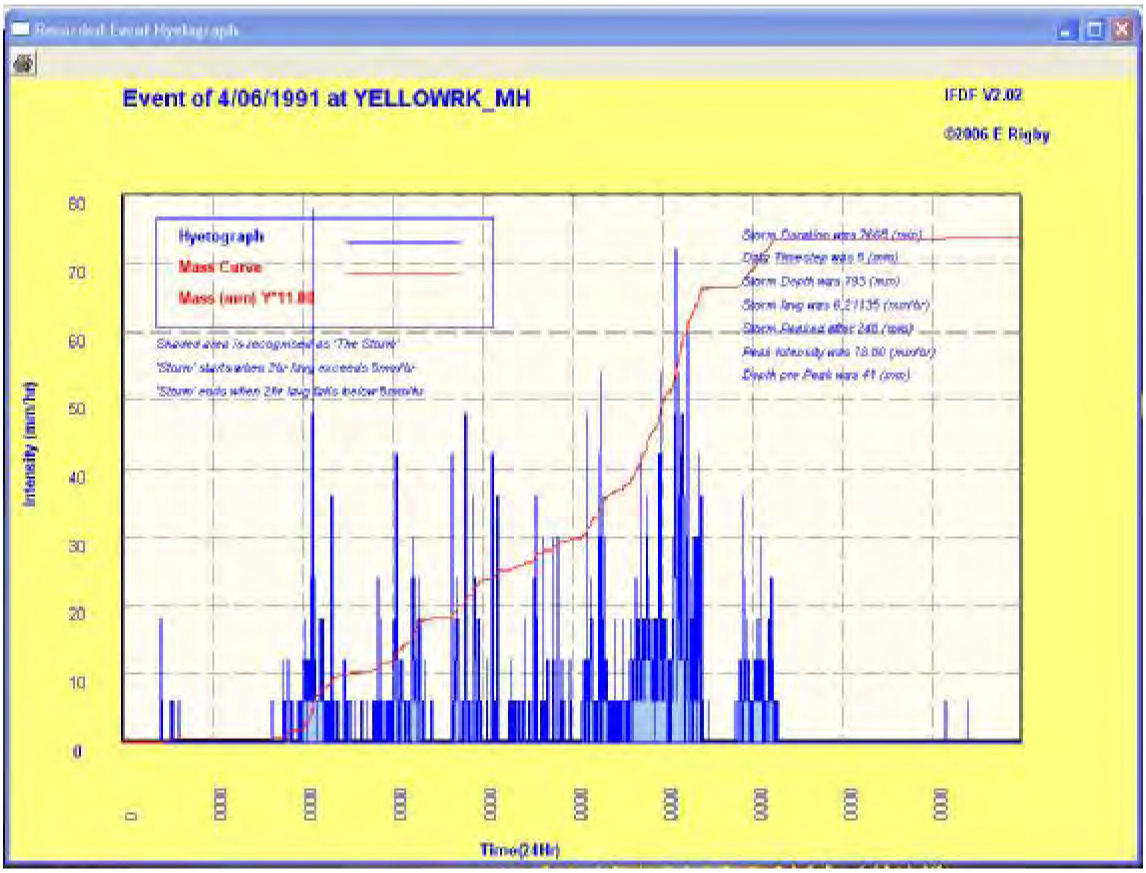
APPENDIX B4. STRUCTURE PHOTOGRAPHY (ctd)



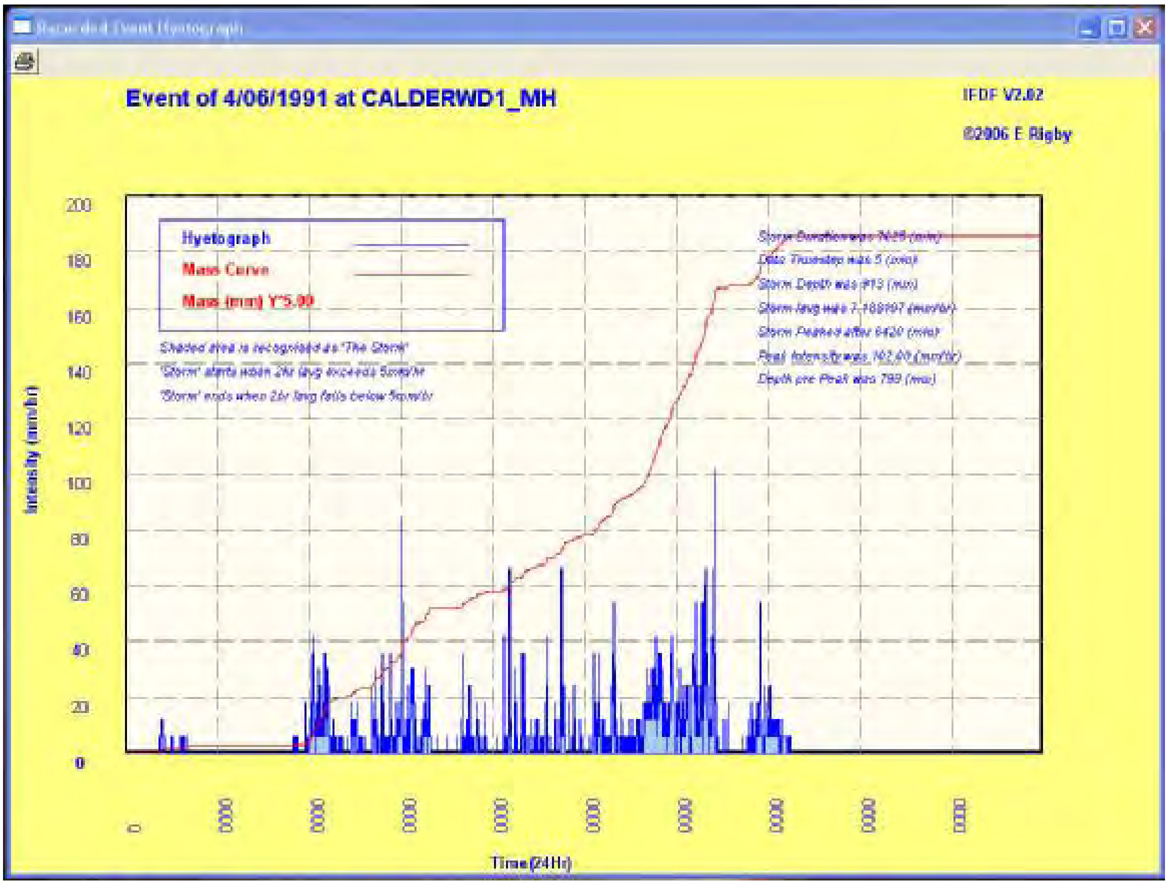


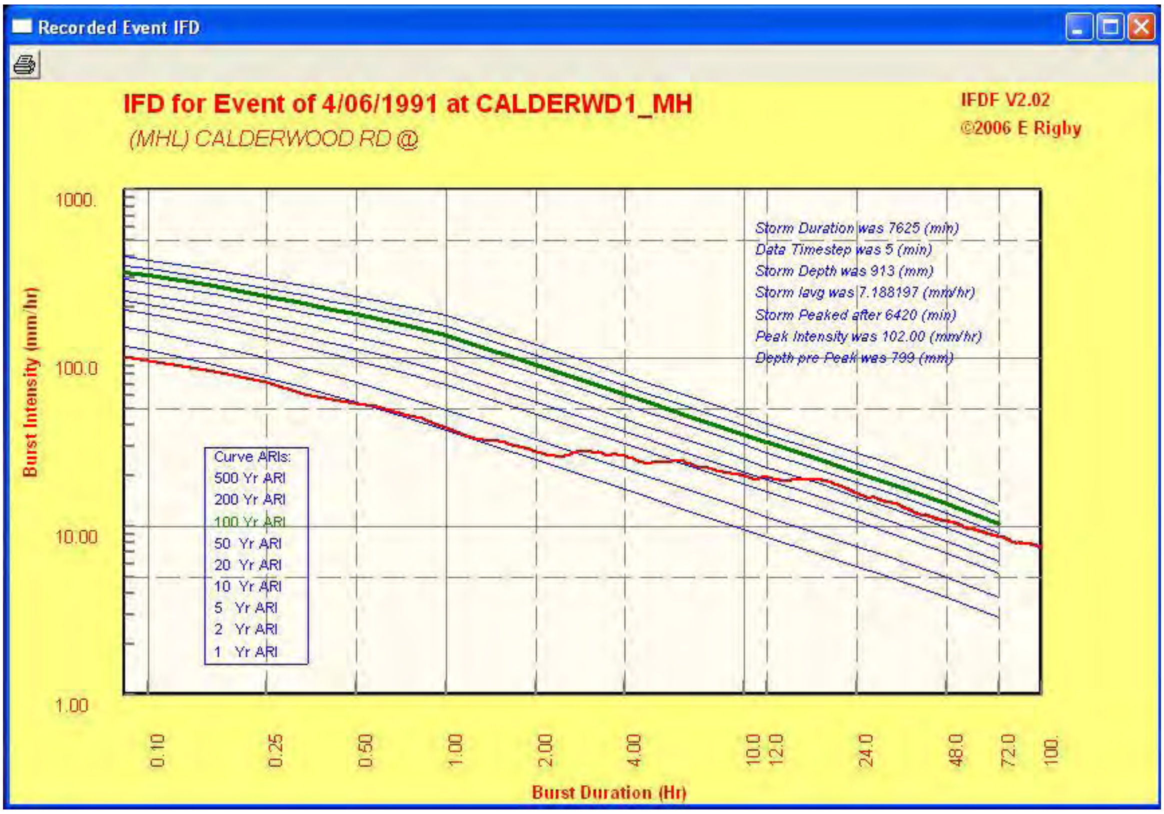
APPENDIX B5. JUNE 1991 HYETOGRAPHS



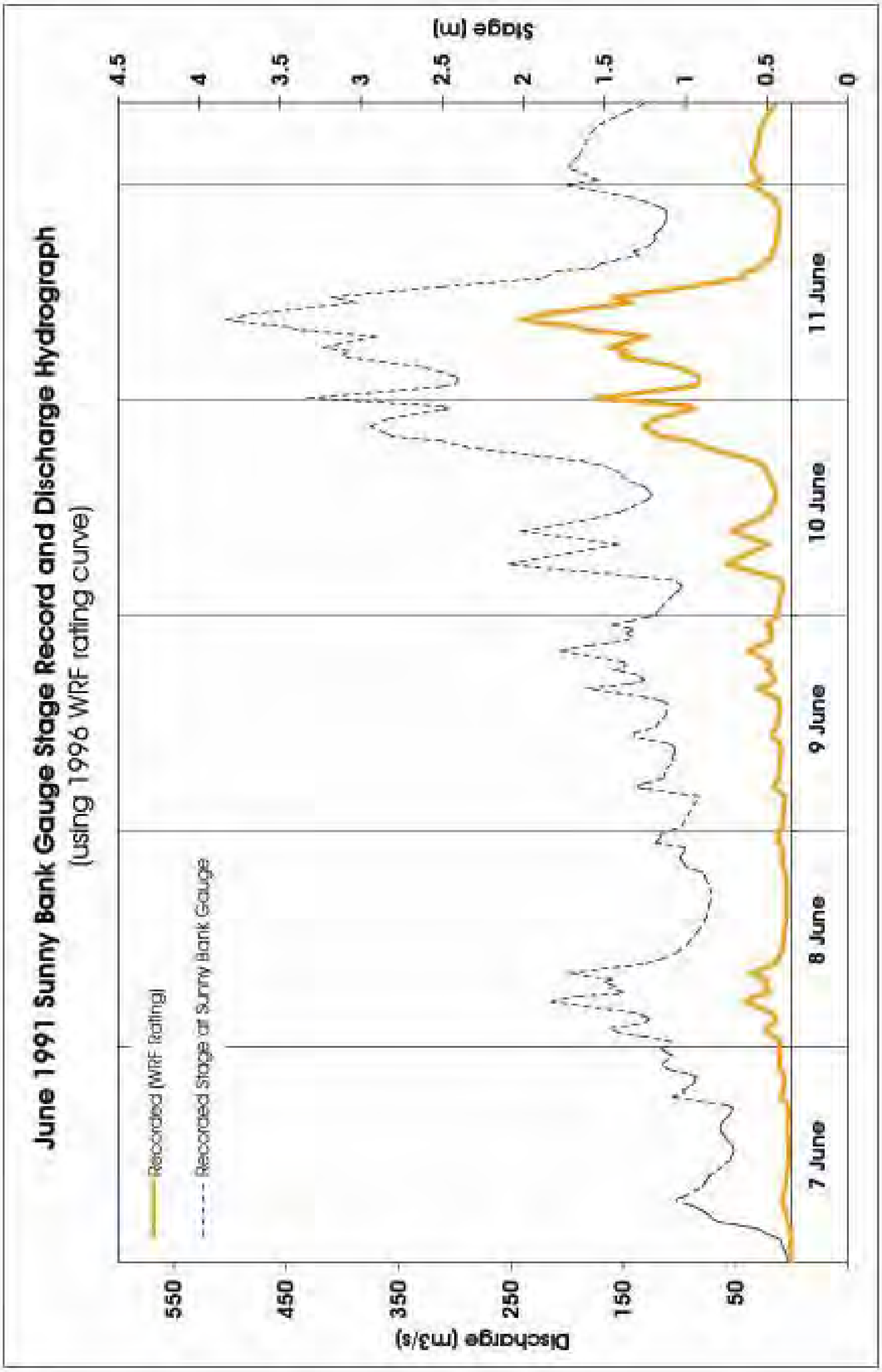


APPENDIX B5. JUNE 1991 HYETOGRAPHS (ctd)

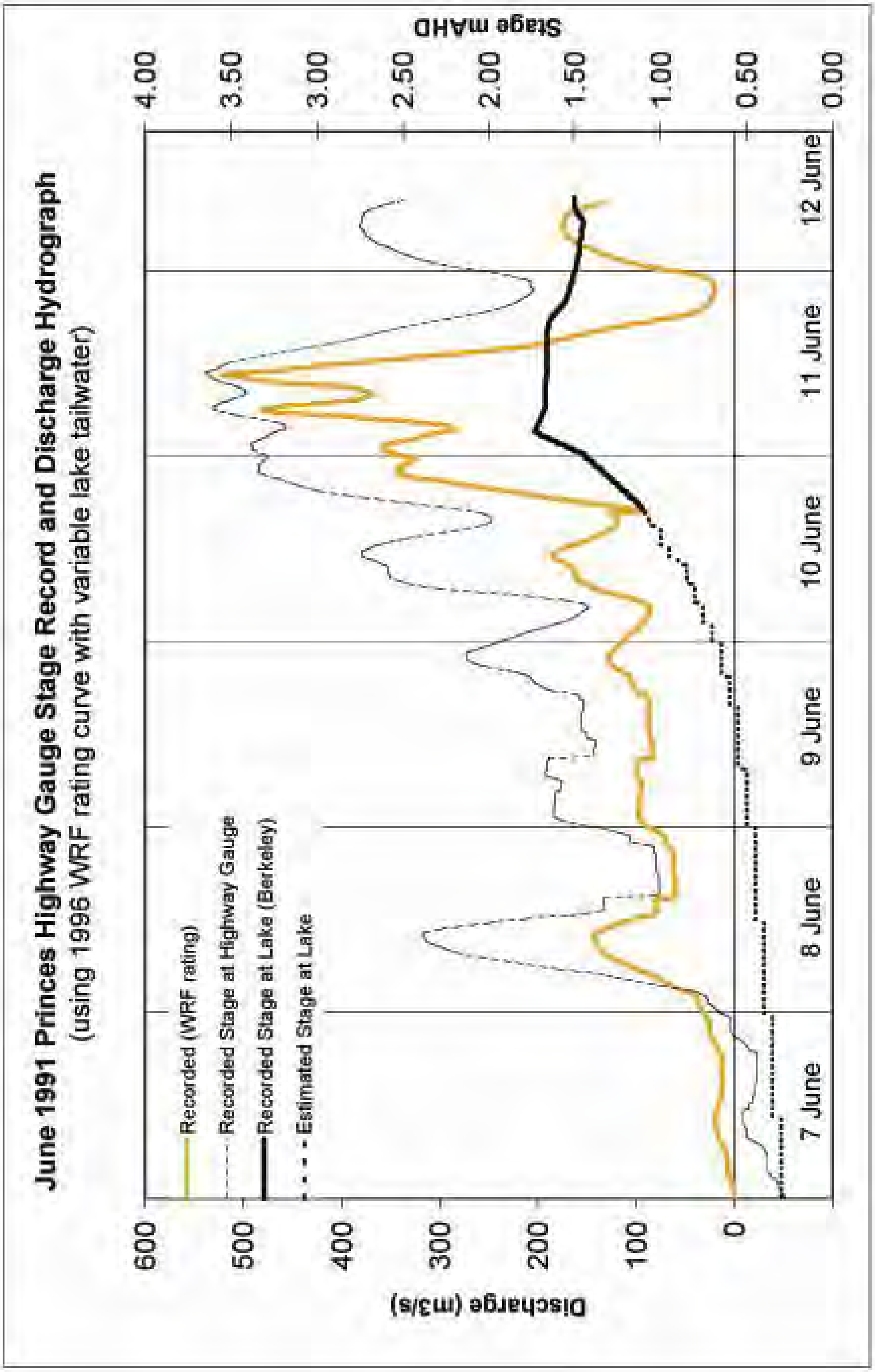




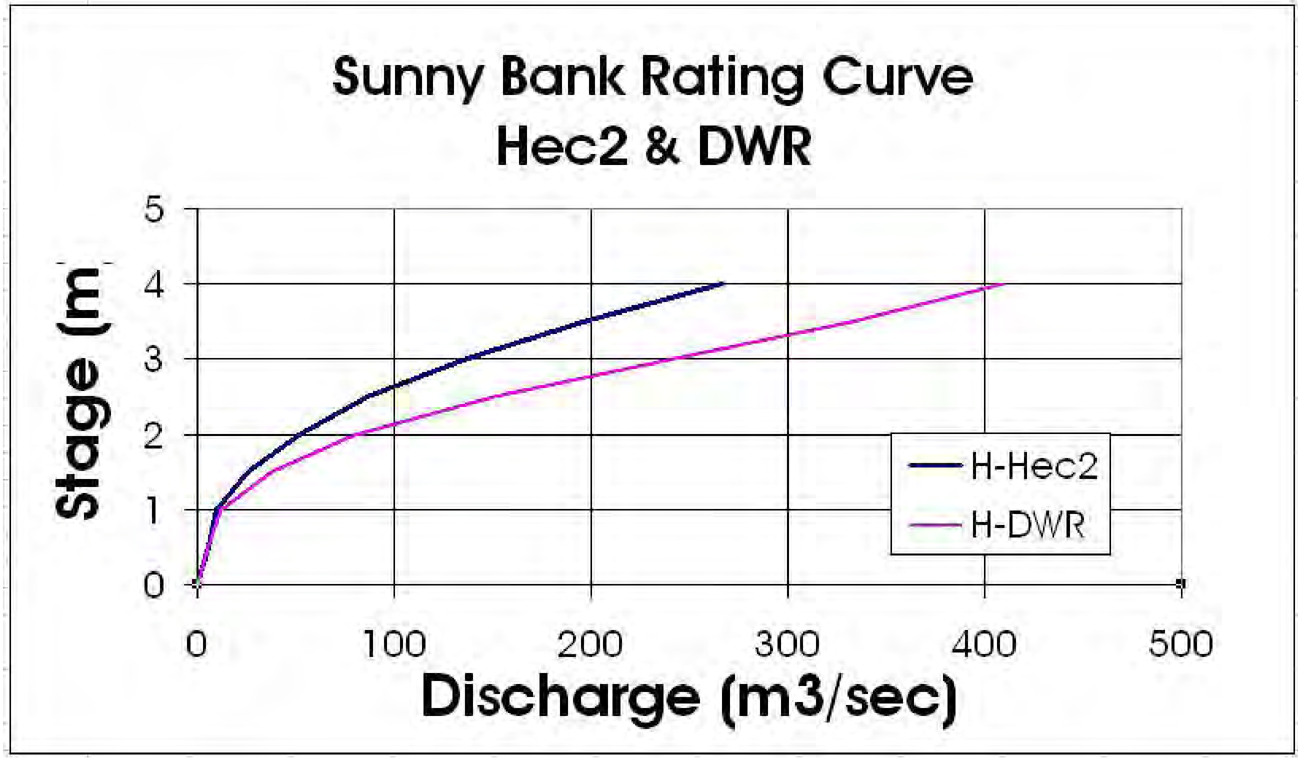
APPENDIX B5. JUNE 1991 HYETOGRAPHS (ctd)



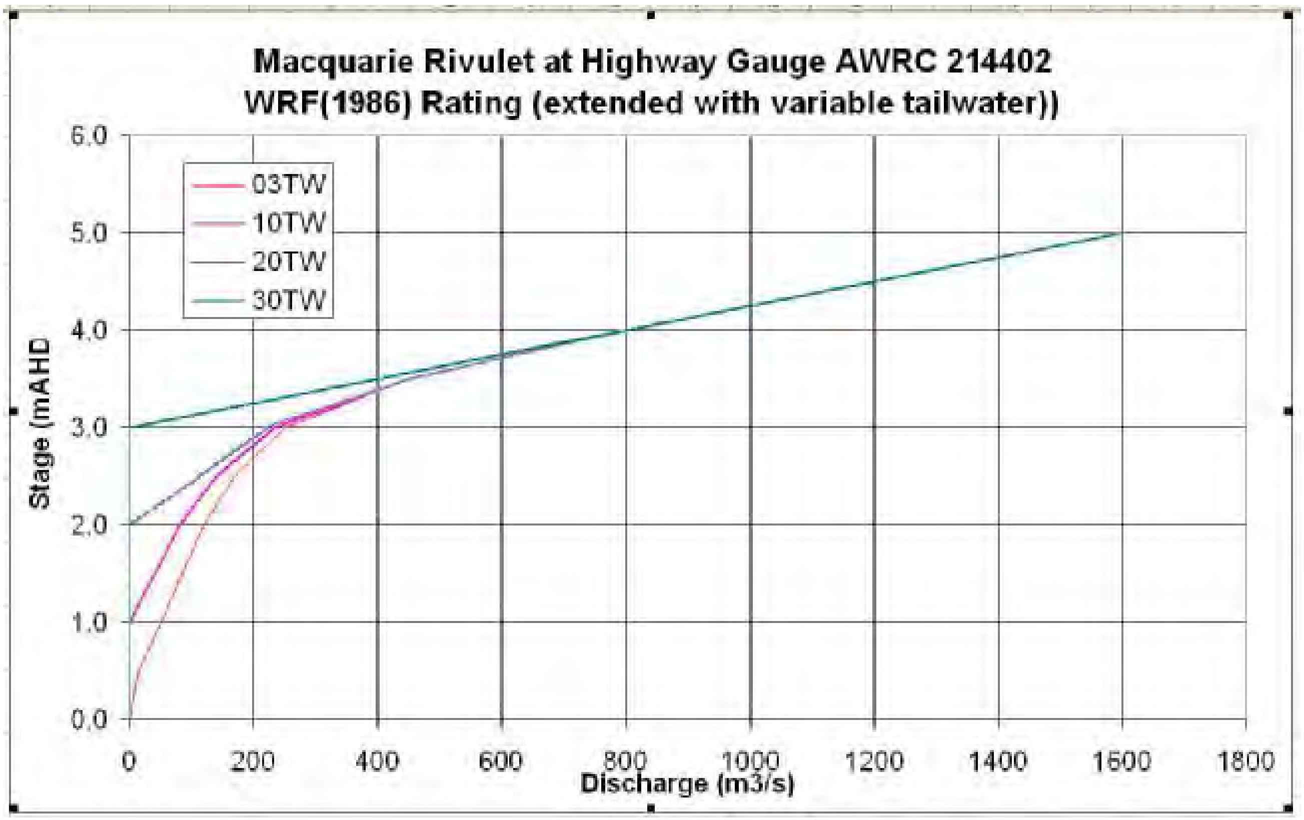
APPENDIX B6. JUNE 1991 ALBION PARK (SUNNYBANK) STAGE RECORD



APPENDIX B7. JUNE 1991 PRINCES HIGHWAY STAGE RECORD



APPENDIX B8. ALBION PARK (SUNNYBANK) RATING CURVE



APPENDIX B9. PRINCES HIGHWAY RATING CURVE

1..US RAIL BRIDGE (Note afflux above central spans

2..US RAIL BRIDGE (Note afflux above central spans

APPENDIX B 10. JUNE 1991 FLOOD PHOTOGRAPHY (E Rigby)

3..Floodplain DS Rail Bridge

APPENDIX B10. JUNE 1991 FLOOD PHOTOGRAPHY (E Rigby) (ctd)

4.. Between Rail and Highway Bridges From North Bank

APPENDIX B10. JUNE 1991 FLOOD PHOTOGRAPHY (E Rigby) (ctd)

5.. US Princes Highway Bridge From South Bank

Illawarra Highway at Green Meadows

APPENDIX B10. JUNE 1991 FLOOD PHOTOGRAPHY (E Rigby) (ctd)

Rail Bridge - Accumulated Debris After Event From DS South Bank

Rail Bridge - Accumulated Debris After Event From US South Bank

APPENDIX B10. JUNE 1991 FLOOD PHOTOGRAPHY (E Rigby) (ctd)

RECORDED FLOOD LEVELS (DECC)

The Department of Natural Resources (now DECC) operates a continuous stage recorder (CSR) immediately downstream of the Princes Highway road bridge. Tables A.-1 and A-2 provide a summary of the data recorded during the June 1991 flood event.(refer also stage hydrograph plot in Appendix B7)

Table A-1: Recorded Peak Flood Level at Princes Highway CSR

STATION	PEAK LEVEL	TIME OF PEAK	
	(m AHD)	(Hour)	(Date)
Macquarie Rivulet at Princes Highway	3.65	1045	11.6.91

Several Maximum Height Recorders are also maintained by the Department in this catchment. Peak flood levels registered at these gauges are tabulated below.

Table A -.2: Recorded Peak Flood Levels at MHIs

CREEK	LOCATION	RL (m AHD)
Macquarie Rivulet	Princes Highway – D/S	3.600
	Foot of Macquarie Pass – D/S	66.460
	Illawarra Highway at Tongarra Creek – D/S	53.630
	Illawarra Highway at Yellow Rock Creek – D/S	17.610
	“Cricklewood” at Marshall Mt Creek	43.030
	“Riversdale” at Marshall Mt Creek	8.470

Several flood debris marks were surveyed after the event by both the DNR and Shellharbour City Council providing comprehensive flood level information for the Macquarie Rivulet catchment. Table A-3 details these surveyed flood levels.

Table A -3: Recorded Peak Flood Levels From All Sources

NO.	LOCATION	RL (m AHD)
1	CSR Peak Reading – R/B D/S Princes Highway Bridge	3.610
2	Debris line – R/B U/S Princes Highway Bridge	3.645
3	Debris line – R/B U/S Illawarra Highway floodway	3.560
4	Debris line – R/B U/S Illawarra Highway floodway	3.560
5	Debris in tree – R/B U/S near Illawarra Highway	8.320
6	Debris in fence – R/B End of Hamilton Road	9.870
7	Debris in fence – R/B U/S Calderwood Road Bridge	11.410
8	Debris in fence – R/B western fence on farm U/S Calderwood Road	11.490
9	Debris line – L/B D/S Illawarra Highway at Yellow Rock Creek Bridge	17.280
10	Debris line – L/B U/S Illawarra Highway at Yellow Rock Creek Bridge	17.580
11	Debris in tree – D/S R/B Nth Macquarie Road floodway	26.580
12	Debris in fence – L/B D/S Tongarra Road cul on Central Frazers Creek	6.390

13	Debris in fence – L/B U/S Tongarra Road cul on Central Frazers Creek	6.570
14	Debris line – L/B D/S Tongarra Road Bridge on East Frazers Creek	7.865
15	Debris line – L/B U/S Tongarra Road Bridge on East Frazers Creek	8.715
16	Debris line – L/B U/S Illawarra Highway cul near Taylors Road	6.075
17	Debris line – L/B 100 m U/S Illawarra Highway cul near Taylors Road	6.220
18	Debris in tree – L/B D/S Cascading Basin on West Frazers Creek	9.750
19	Debris line – R/B U/S Cascading Basin on West Frazers Creek	10.100
20	Debris in tree – R/B 150 m D/S Terry Street cul on West Frazers Creek	10.860
21	Debris line – L/B D/S Terry St cul on West Frazers Creek	12.970
22	Debris line – L/B U/S Terry St cul on West Frazers Creek	13.800
23	Debris line – R/B D/S Simpson Pde cul on West Frazers Creek	22.550
24	Debris in fence – R/B U/S Simpson Pde on West Frazers Creek	24.210
25	Debris in tree – L/B at end of Frazers Cres on Central Frazers Creek	8.620
26	Debris in tree – L/B 50 m D/S of causeway to Polo Club on Centl Frazers Ck	13.830
27	Debris in fence – L/B U/S footbridge end of Hughes Drv on Centl Frazers Ck	14.090
28	Debris line – L/B D/S Retarding Basin at end of Smith Ave	16.300
29	Debris line – L/B D/S Terry St cul on Central Frazers Creek	24.600
30	Debris in tree – L/B northern end of Polo Field on East Frazers Creek	12.845
31	Debris in tree – L/B in Polo Field on East Frazer Creek	13.790
32	Debris in tree – L/B D/S footpath at end of Hughes Dr on East Frazers Ck	16.480
33	Debris line – R/B D/S Marshall Mt Road culv	18.150
34	Debris in fence – R/B D/S Marshall Mt Road	18.490
35	Debris line – R/B U/S Marshall Mt Road culv	19.010
36	MHI Recording - L/B D/S Illawarra Highway at foot of Macquarie Pass	66.460
37	MHI Recording - R/B D/S Illawarra Highway at Tongarra Creek	53.630
38	MHI Recording - R/B at "Cricklewood" on Marshall Mt Creek	43.030
39	MHI Recording - R/B at "Riversdale" on Marshall Mt Creek	8.470
40	Debris line - R/B D/S of Highway at gauge	3.570
41	Debris line - R/B 150m D/S of Highway	3.440
42	Debris line - R/B 250m D/S of Highway	3.400
43	Debris line - R/B U/S of Railway	3.000
44	Debris in fence - R/B D/S of Railway	3.040
45	U/S Princes Highway	3.725
46	100m U/S Princes Highway	4.140
47	U/S Princes Highway on Albion Creek	2.870
48	D/S Railway on Albion Creek	1.900
49	Pedestrian Bridge near Pollock Crescent	12.360
50	Taylor Rd 150m west of Illawarra Hway	6.100
51	R/B U/S culvert on Central Frazers Ck	6.530
52	L/B Central Frazers Ck 150m U/S of Tongarra Rd	7.080
53	L/B West Frazers Ck U/S of Terry St	13.820
54	West Frazers Creek near end of Propane St	16.560
55	West Frazers Creek U/S Simpsons Pde	23.985
56	Direct Observation by owner - Macriv R/B rear of Meadow View dairy	4.690

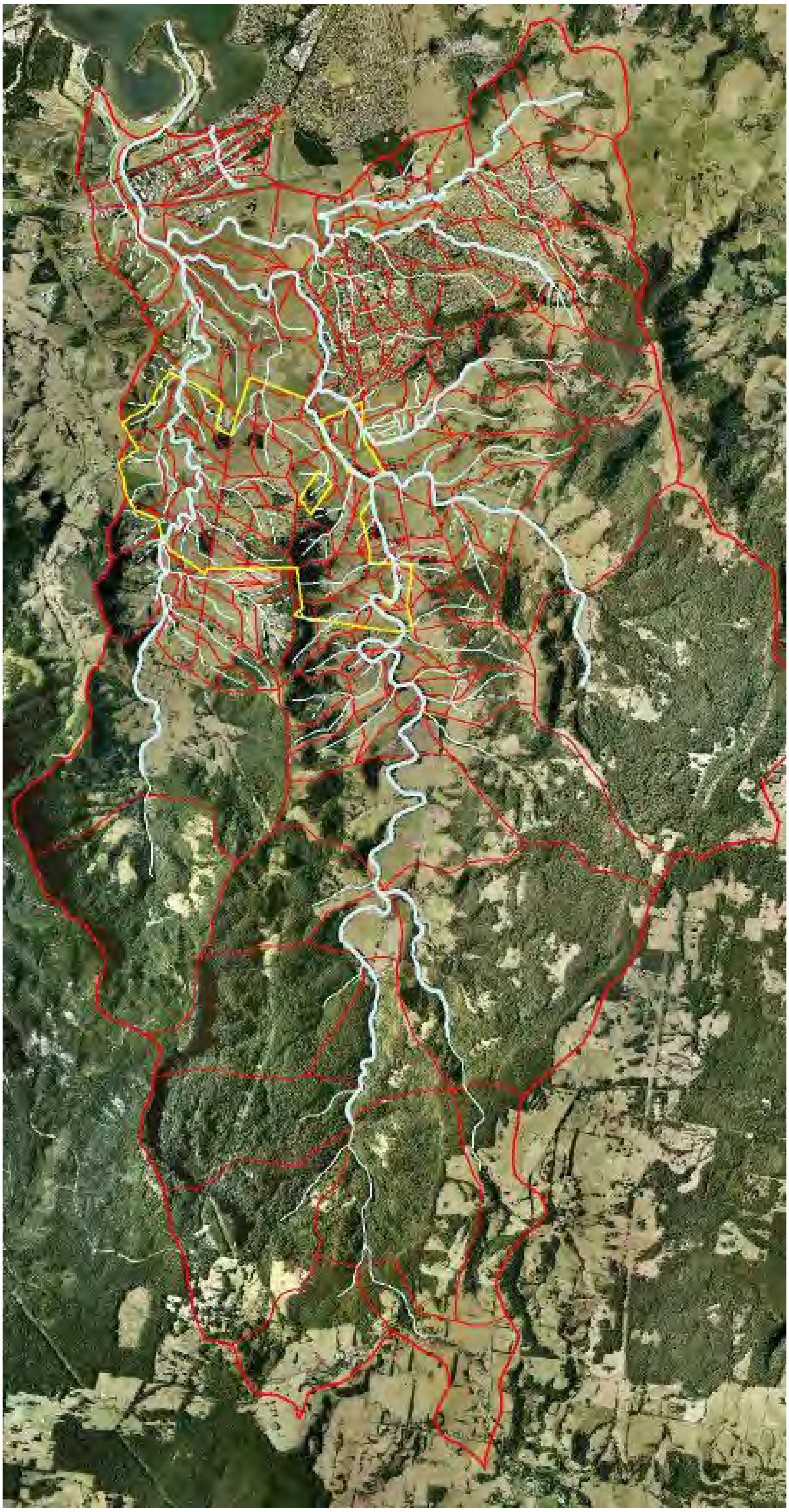
APPENDIX B11. JUNE 1991 RECORDED FLOOD LEVELS

HYDROLOGIC MODEL ESTABLISHMENT

C.1 **Hydrologic Model Layout**
C.2 **Hydrologic Model Impervious Cover**
C.3 **Hydrologic Model Storages & Diversions**

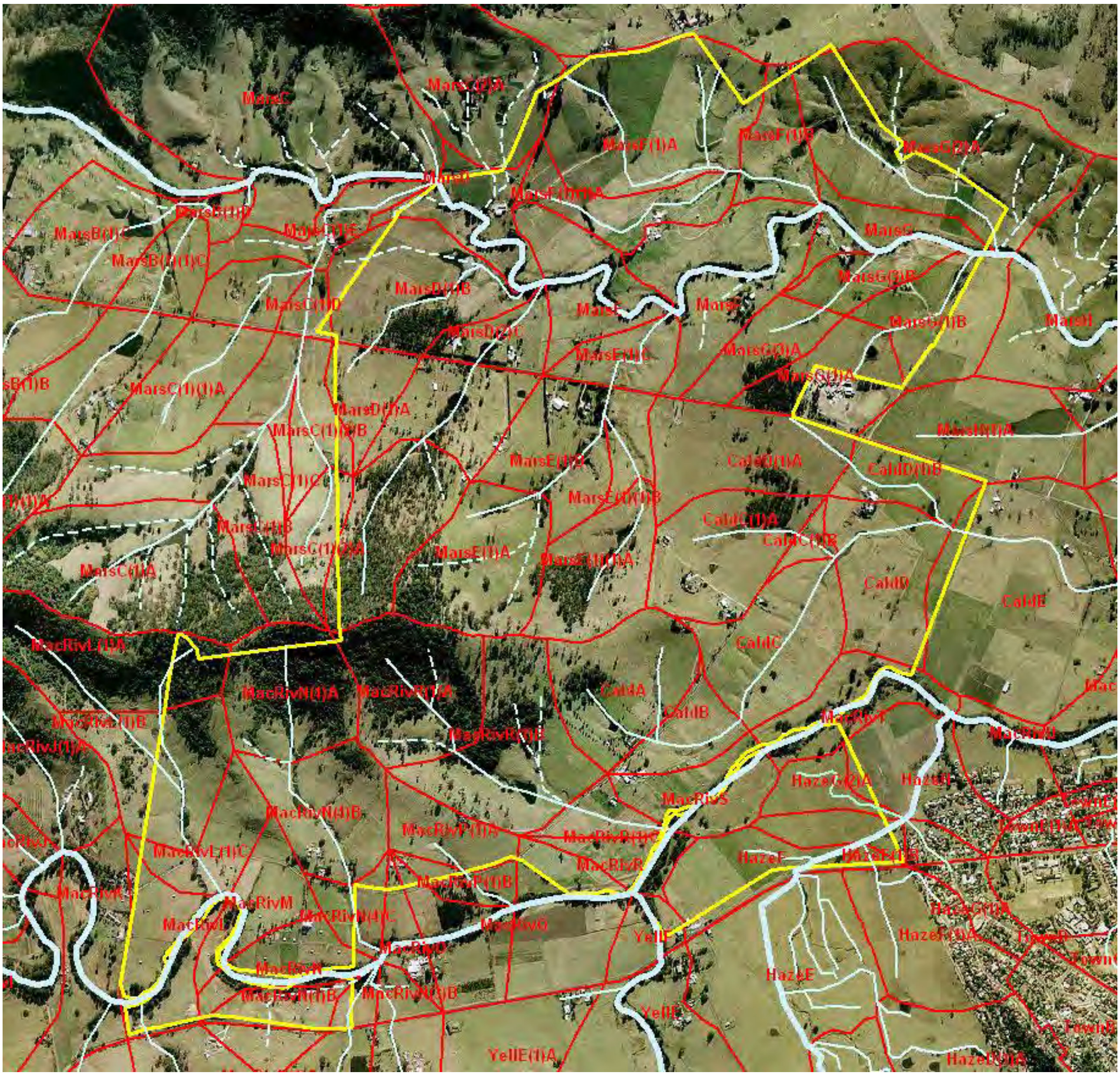
C
C
C
C

APPENDIX C



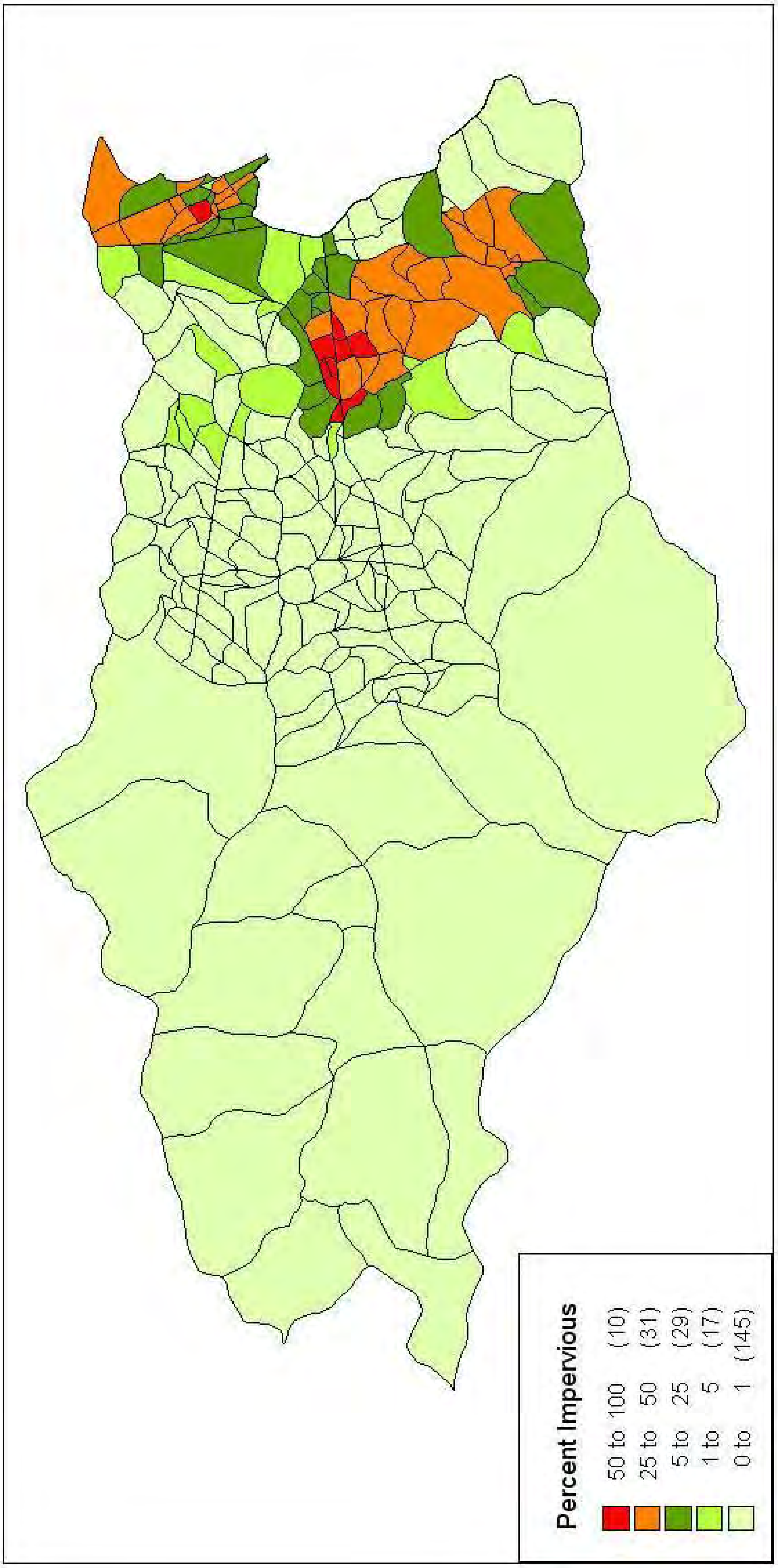
CATCHMENT LAYOUT

APPENDIX C1b HYDROLOGIC MODEL LAYOUT

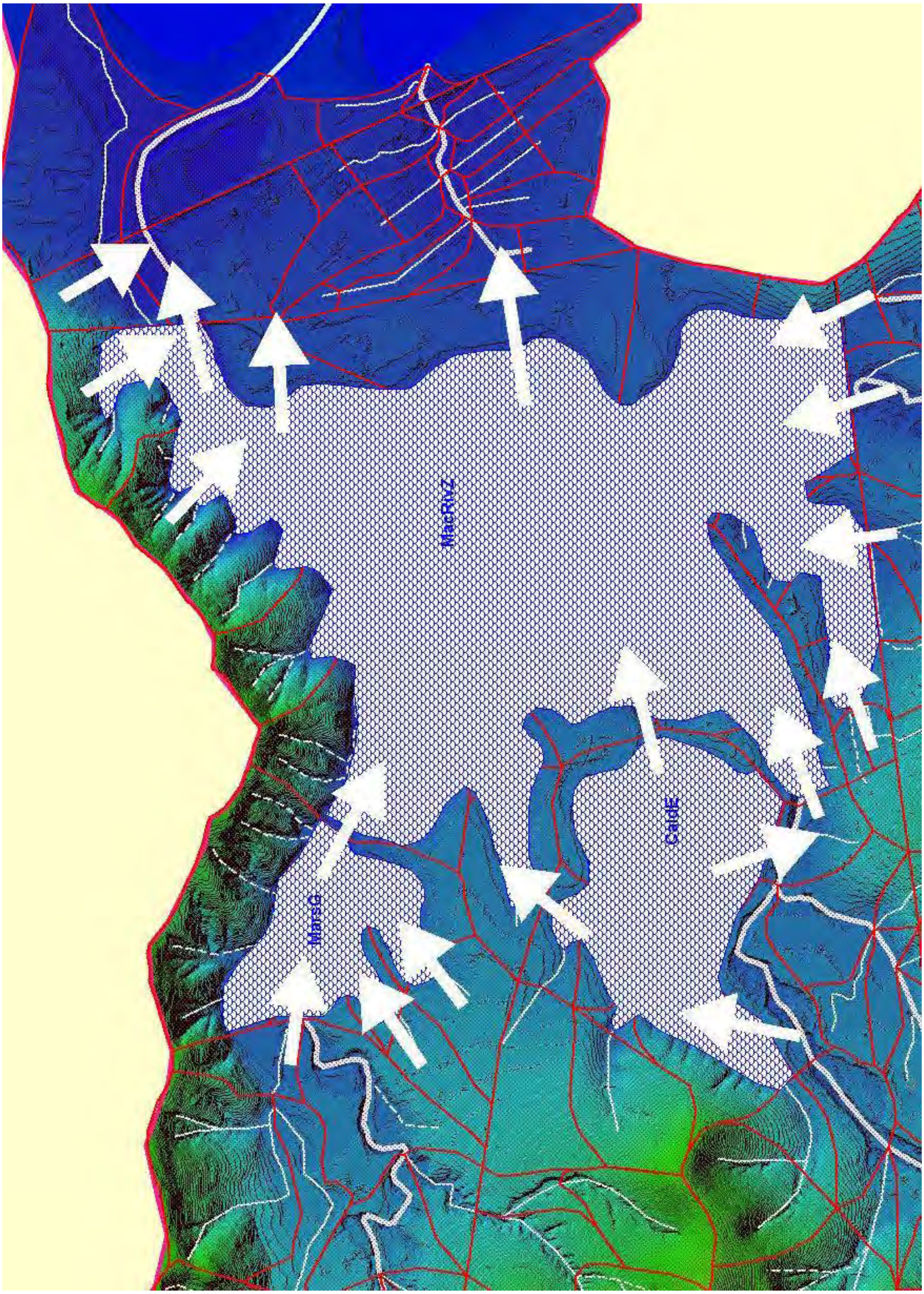


CATCHMENT LAYOUT - SITE ENLARGEMENT

APPENDIX C1b HYDROLOGIC MODEL LAYOUT



APPENDIX C2, HYDROLOGIC MODEL IMPERVIOUS COVER



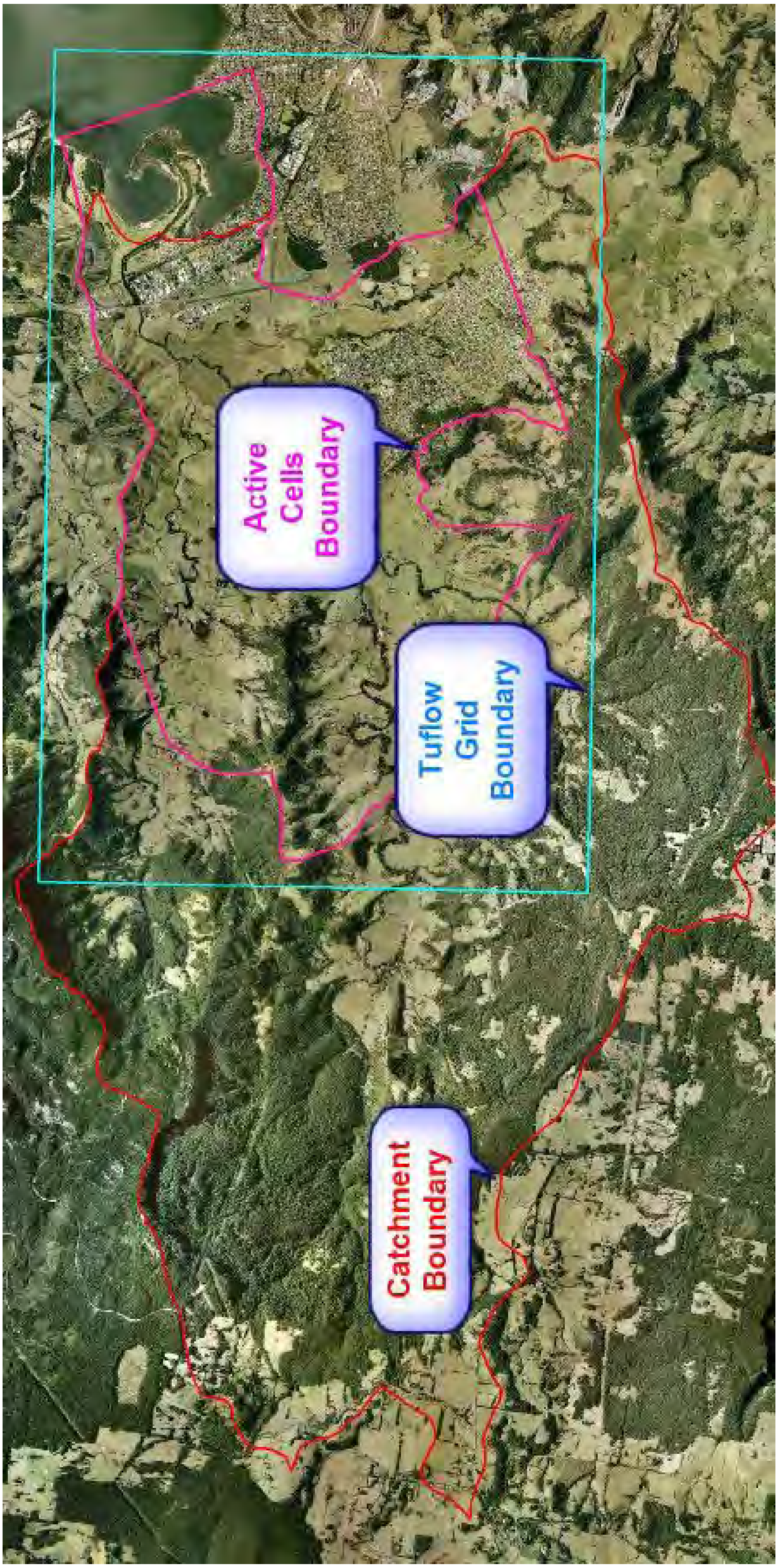
APPENDIX C3. HYDROLOGIC MODEL STORAGES & DIVERSIONS

HYDRODYNAMIC MODEL ESTABLISHMENT

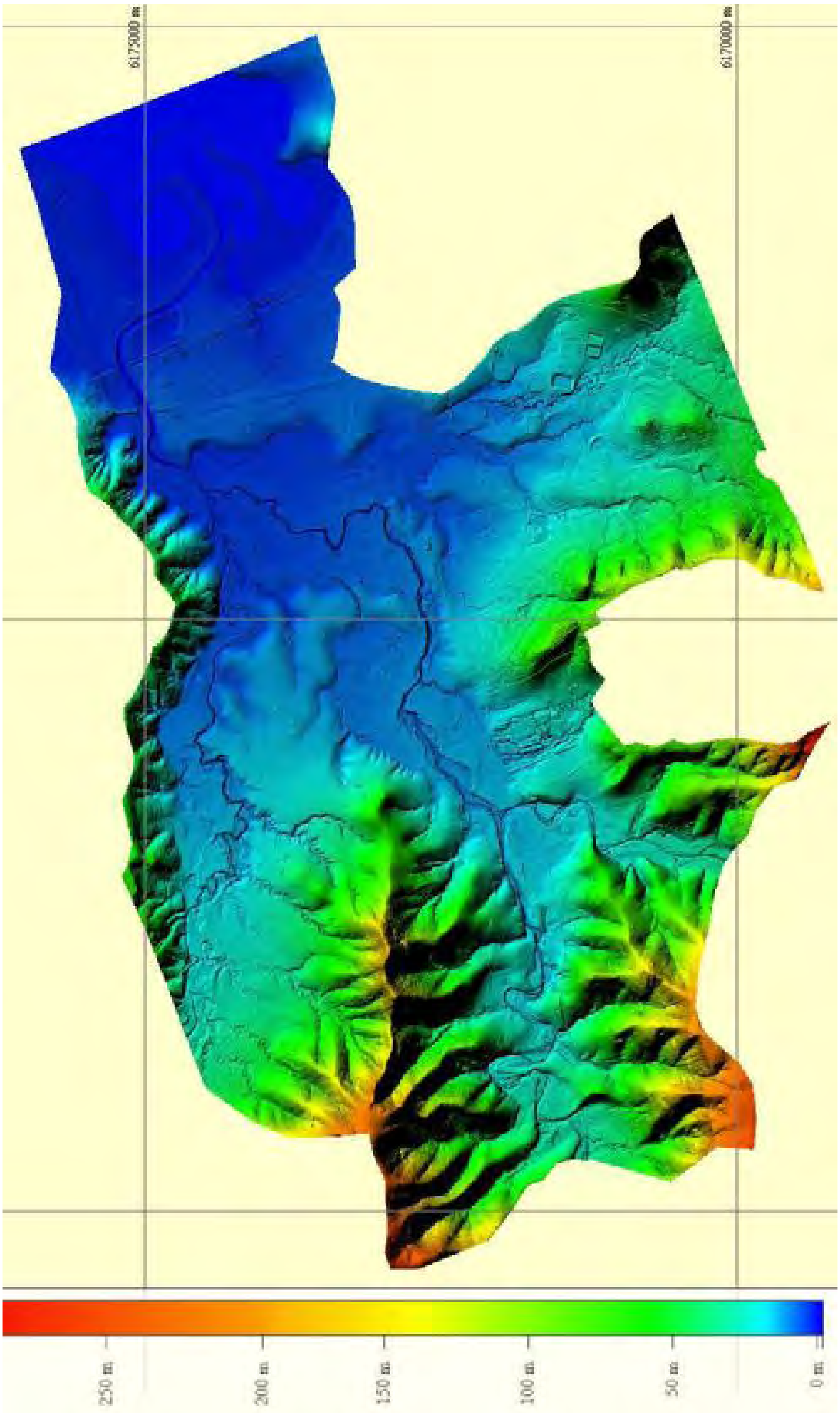
D.1 **Hydrodynamic Model Extents**
D.2 **Hydrodynamic ModelTopography**
D.3 **Hydrodynamic Model Surface Roughness**
D.4 **Hydrodynamic Model Structures**
D.5 **Hydrodynamic Model Boundary Conditions**

D
D
D
D

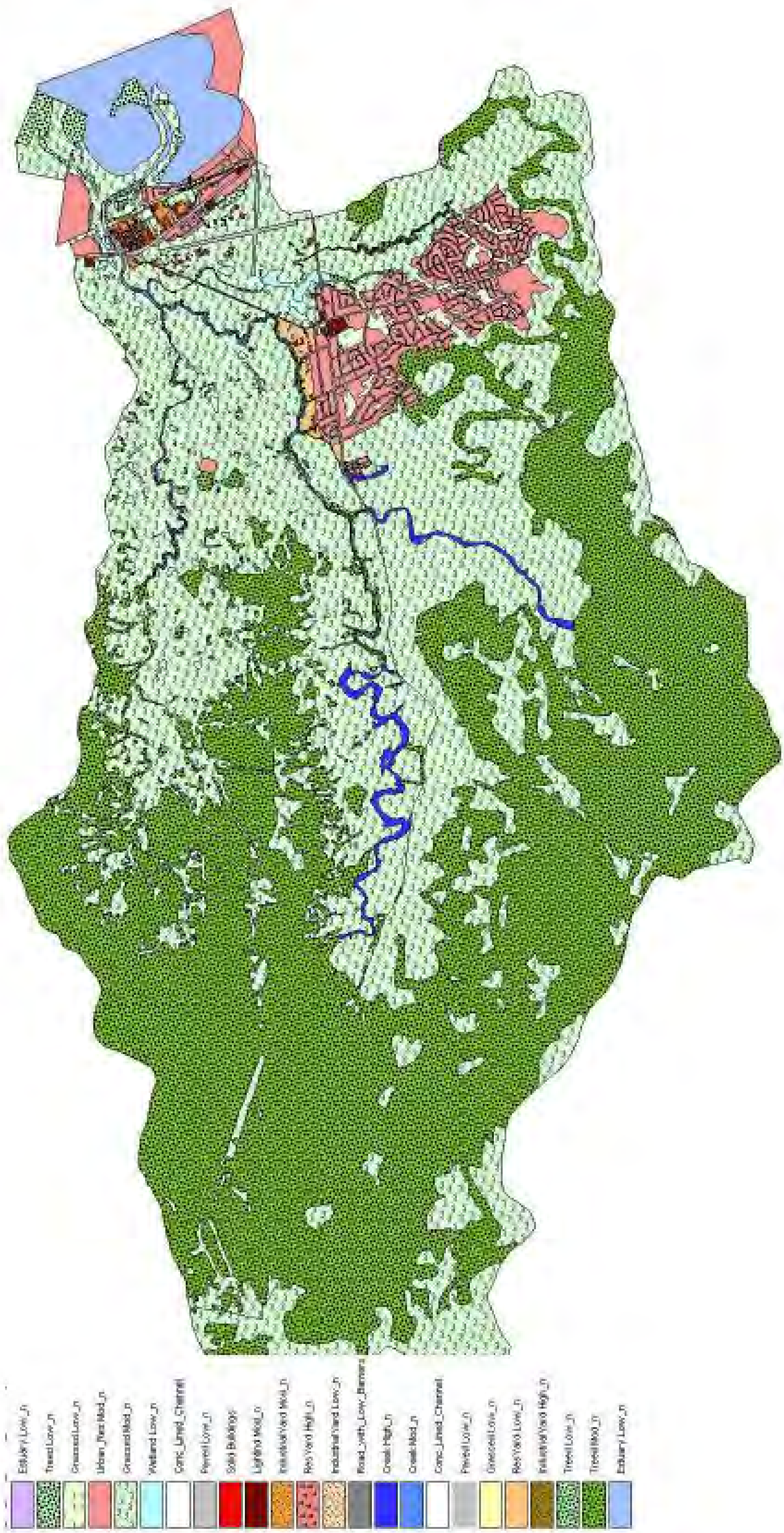
APPENDIX D



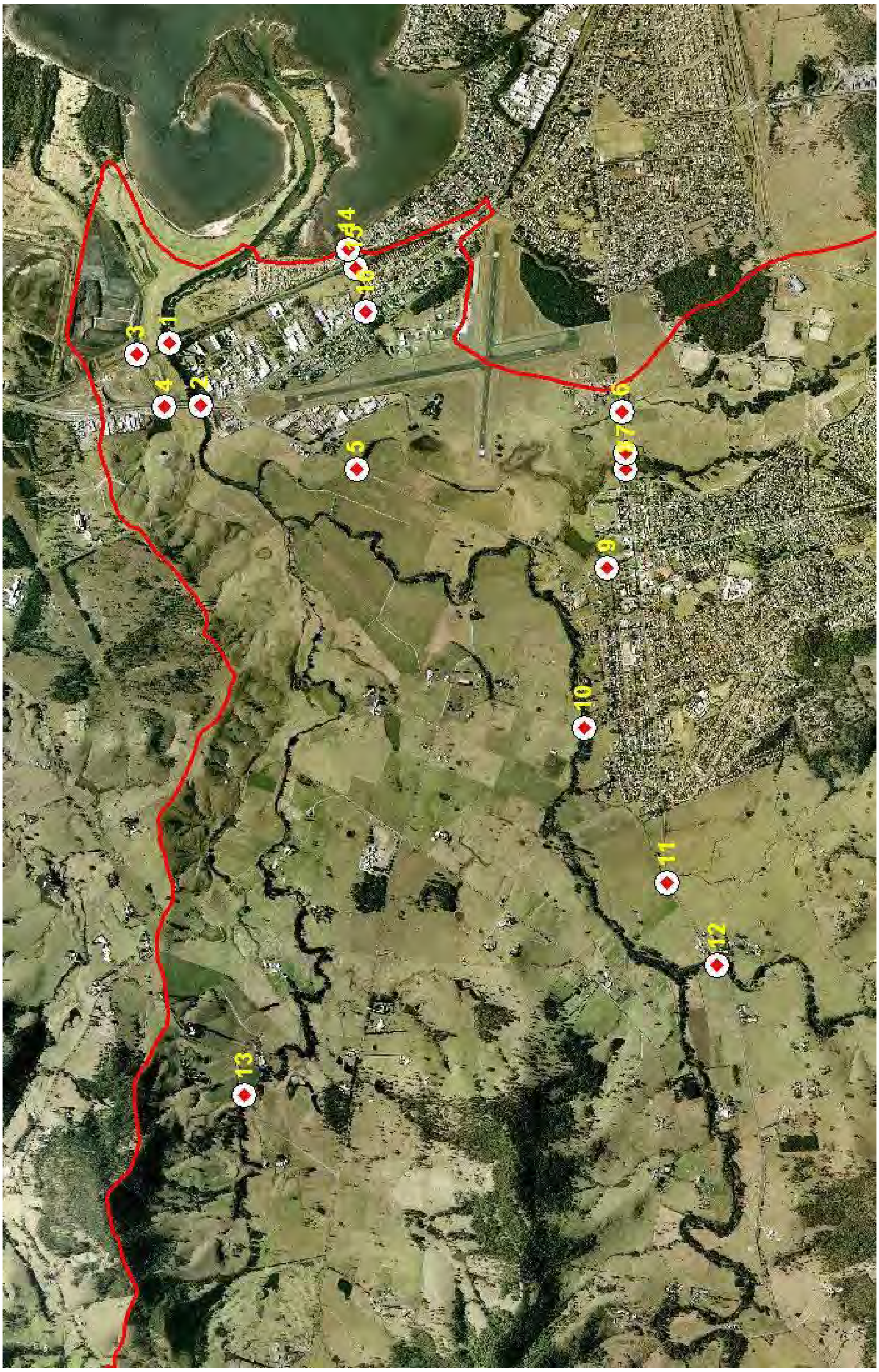
APPENDIX D1: HYDRODYNAMIC MODEL EXTENTS



APPENDIX D2: HYDRODYNAMIC MODEL TOPOGRAPHY

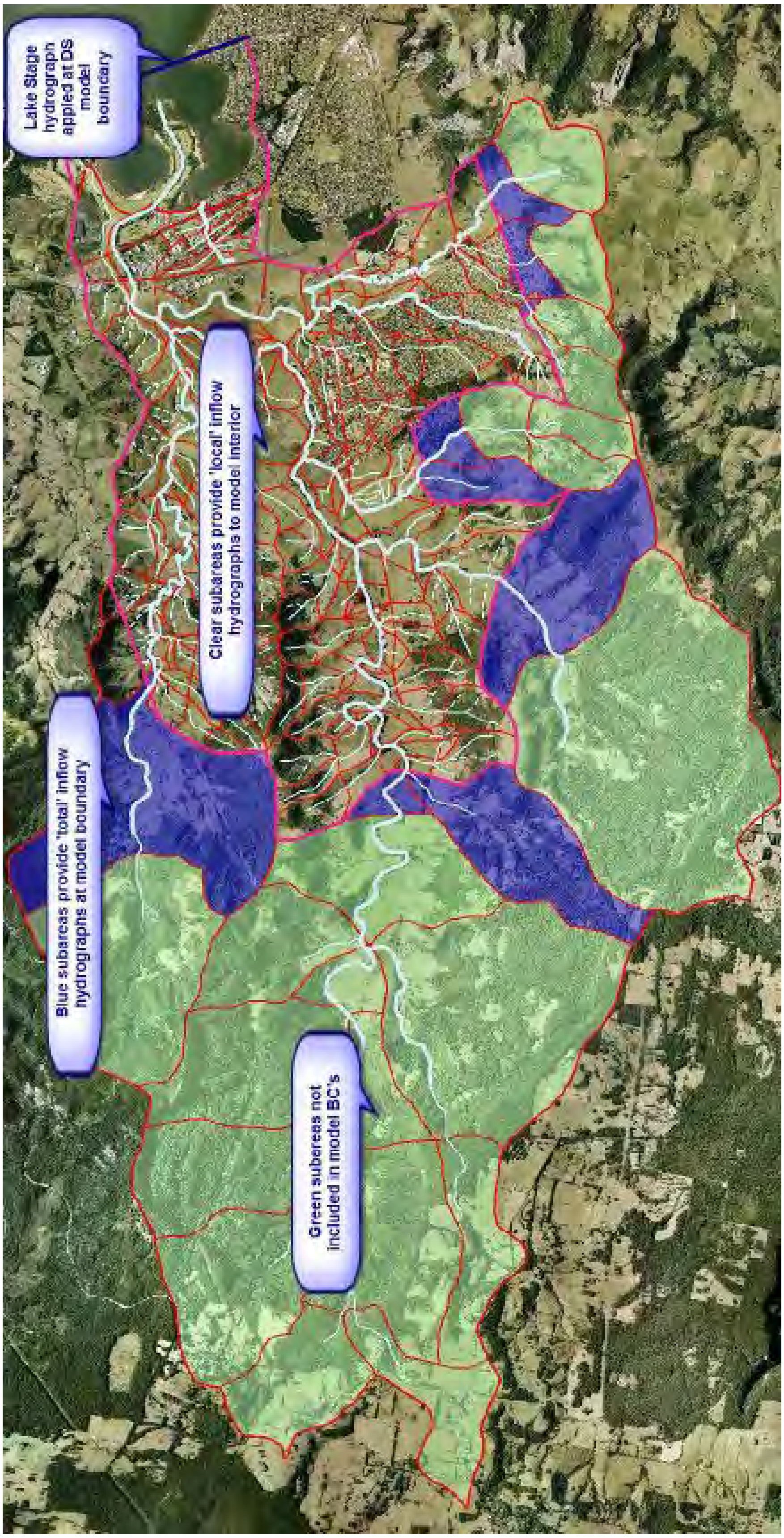


APPENDIX D3: HYDRODYNAMIC MODEL SURFACE ROUGHNESS(2009)



For details of each structure refer Appendix B4

APPENDIX D4: HYDRODYNAMIC MODEL STRUCTURES



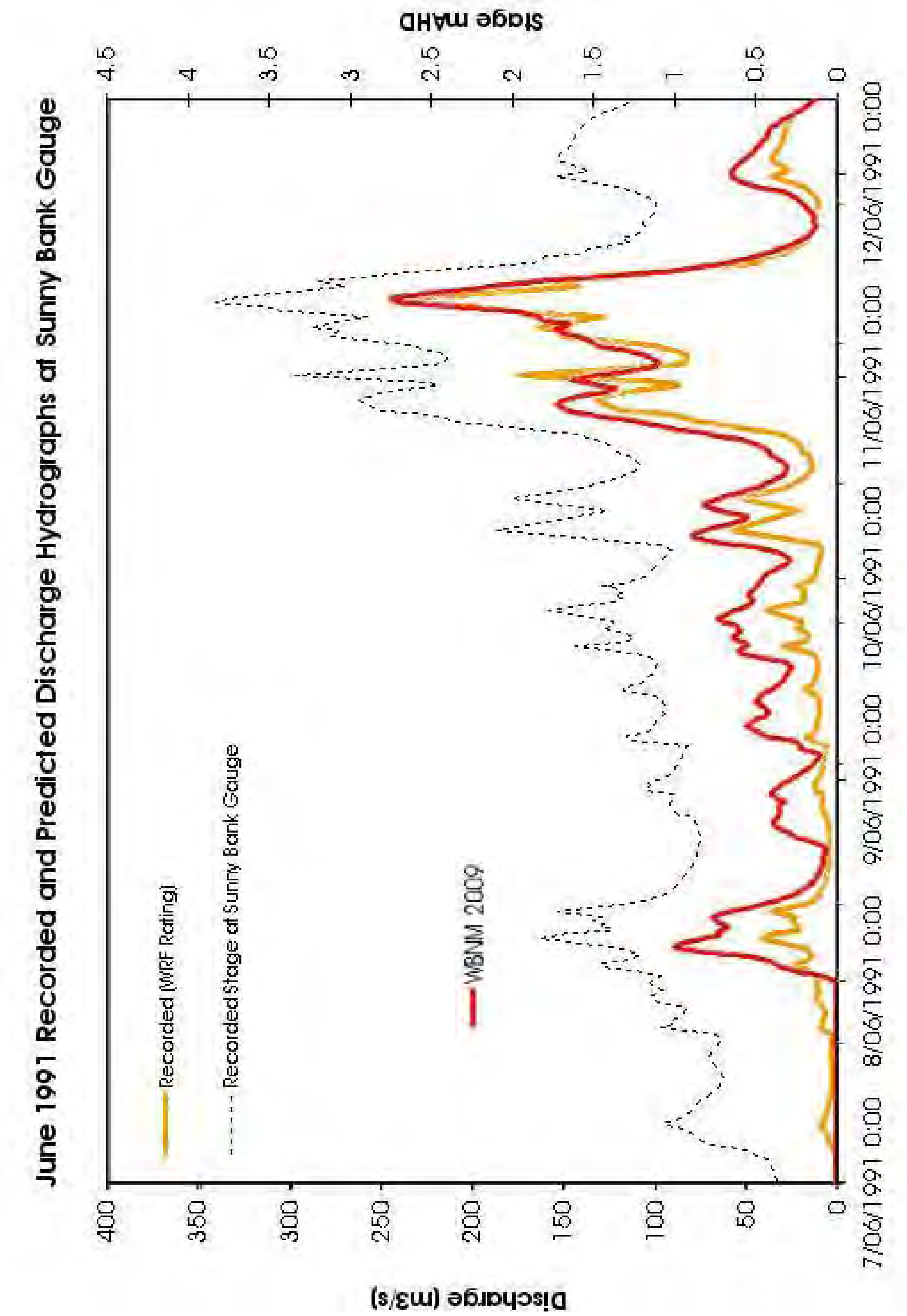
APPENDIX D5: HYDRODYNAMIC MODEL BOUNDARY CONDITIONS

MODEL CALIBRATION

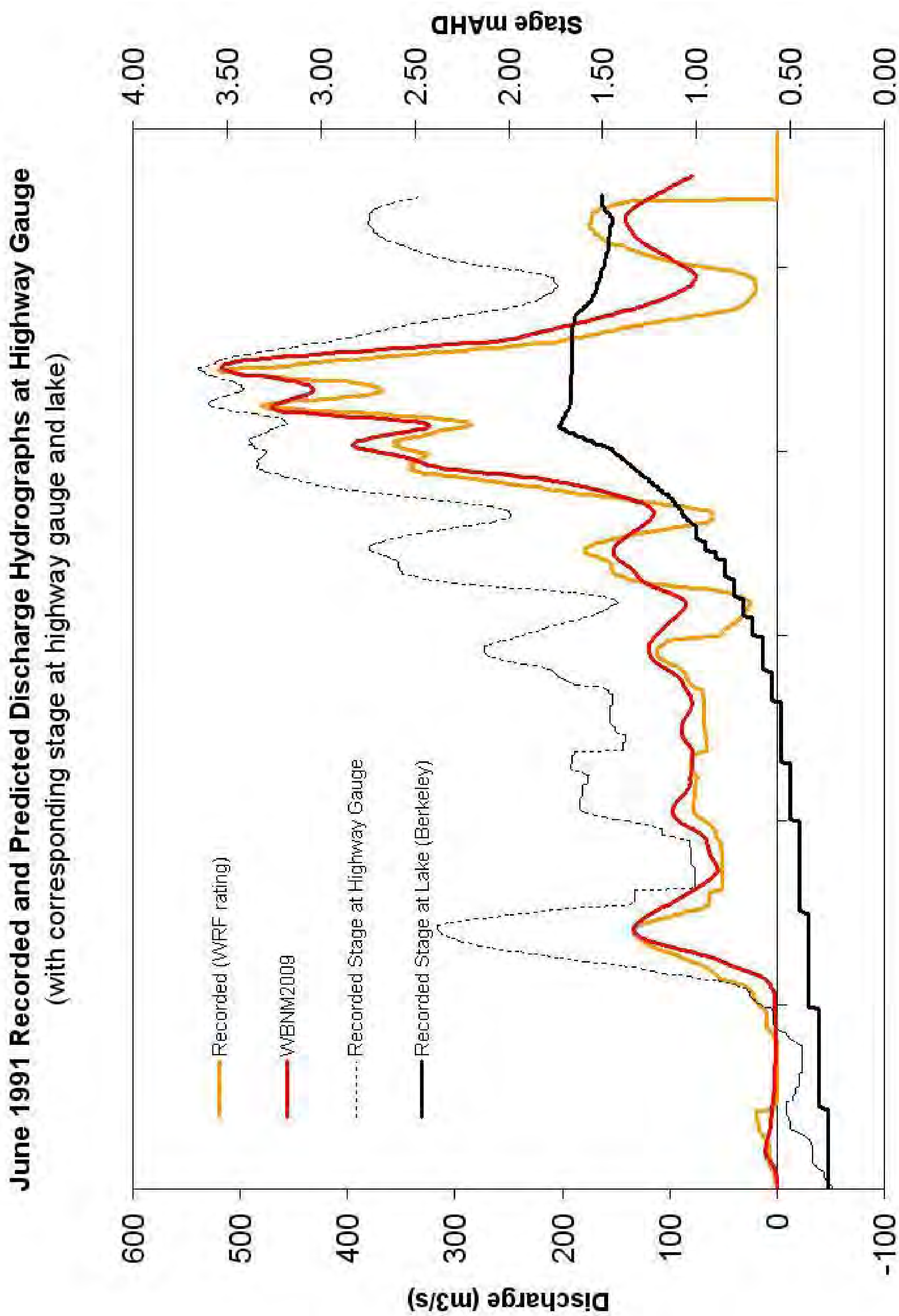
E.1 **Recorded –v- Modelled June91 Hydrograph at SB**
E.2 **Recorded –v- Modelled June91 Hydrograph at PH**
E.3 **Recorded –v- Modelled June91 Peak Flood Surface**
E 4 **Adopted Hydrologic Parameters**
E 5 **Adopted Surface Roughness Values**

E
E
E
E

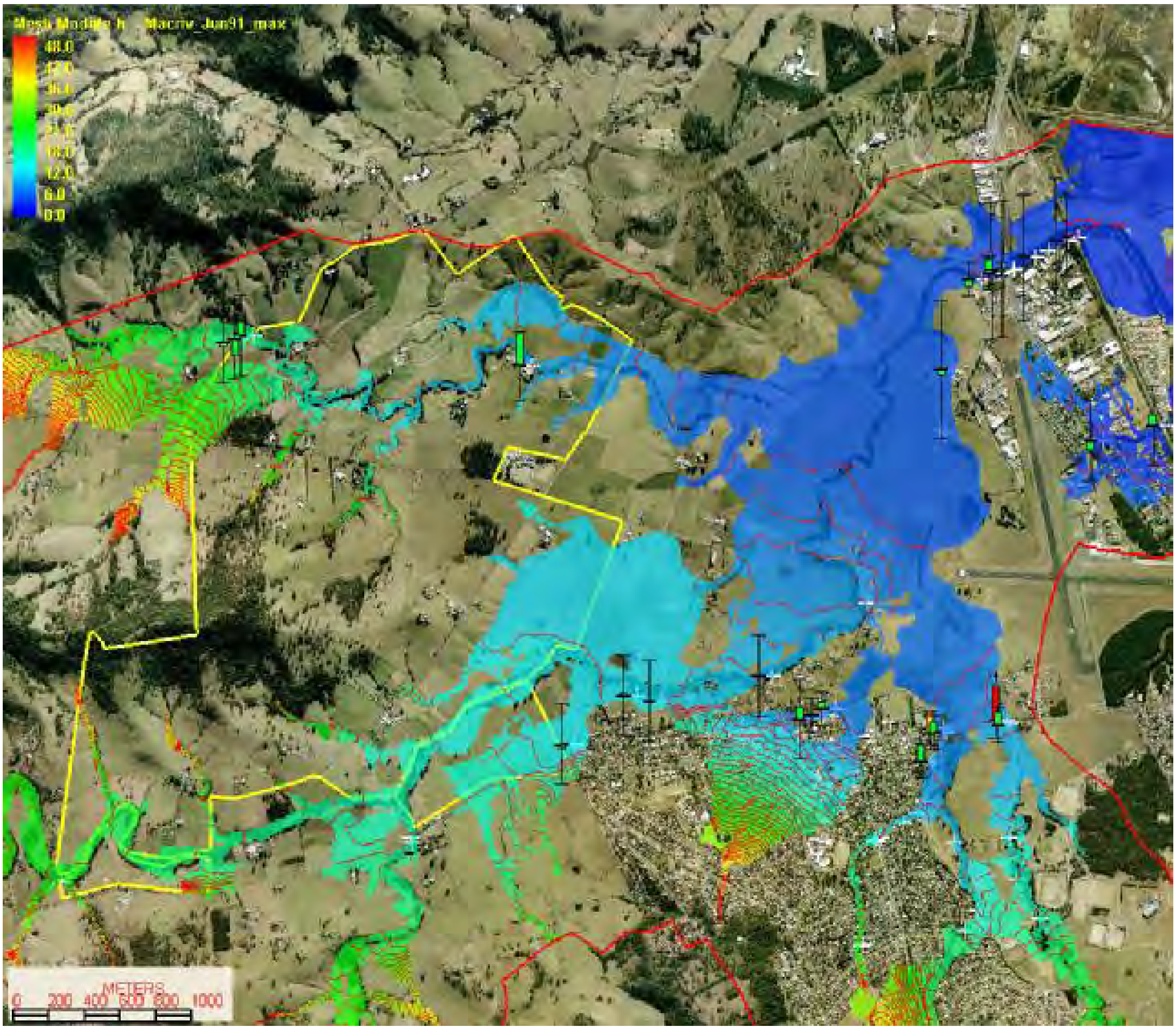
APPENDIX E



APPENDIX E1: RECORDED –v- MODELLED JUNE 1991 HYDROGRAPH SB



APPENDIX E2: RECORDED –v- MODELLED JUNE 1991 HYDROGRAPH PH



Modelled June 1991 Flood Surface

SMS CALIIBRATION PLOT NOTES

In the above SMS calibration plot, each calibration target is drawn an amount equal to the likely error above and below the recorded data value The difference between the simulated flood surface value and recorded value is plotted as a scaled coloured bar. Where coloured bar is plotted below the target mean, this corresponds to a simulated surface level below the recorded value and vice-versa when above. Where the simulated surface is within the likely error band for the recorded value, the colour bar (scaled difference) is plotted green. When the simulated level falls outside of the likely error band but lies within a band that is twice the likely error, the bar is plotted yellow and if it falls outside of the doubled error band, the bar is plotted red. In calibration the objective is to obtain all bars green, with bars plotted equally above and below the recorded values.

APPENDIX E3: RECORDED –v- MODELLED JUNE 1991 FLOOD SURFACE

ADOPTED HYDROLOGIC PARAMETERS

PARAMETER	CONDITION	CALIBRATION	DESIGN
Initial Loss (IL perv)	-	150mm	15mm
Initial Loss(Il Imp)	-	1mm	1mm
Cont Loss (CL:R)	-	2.5mm/hr	2.5mm/hr
Catcment Lag (C)	-	1.3	1.3
Imp Lag Factor	-	0.1	0.1
Stream Lag Factor	Natural	1.0	1.0
Stream Lag Factor	Earth lined channels	0.5	0.5
Stream Lag Factor	Conc lined channels	0.33	0.33
Init Storage Levels	All	Empty	Empty

APPENDIX E4: ADOPTED HYDROLOGIC PARAMETERS

ADOPTED SURFACE ROUGHNESS VALUES
(extracted from Tuflow 2d_mat.tmf)

SURFACE	d1	n1	d2	n2	DESCRIPTION
Grassed Low_n	0.05	0.075	0.25	0.020	mown or well grazed 0.05 stubble, low undulations
Grassed Mod_n	0.15	0.100	0.75	0.030	mixed areas of slashed/grazed grassland with some shrubs and/or taller grass clumps
Grassed High_n	0.50	0.100	2.50	0.040	tall stiff grass with significant areas of clumped shrubs
Grassed Swale	0.05	0.075	0.25	0.020	mown or grazed 0.05 stubble (sim Grassed low_n)
Trees Low_n	1.00	0.050	5.00	0.050	moderate density little underbrush typically easy to walk thru off track
Trees Mod_n	1.00	0.100	5.00	0.075	moderate density some underbrush occasional fallen limb typically difficult to walk thru off track
Trees High_n	1.00	0.200	5.00	0.100	High density substantial underbrush and fallen limbs typically cannot walk thru off track
Landscaped Low_n	0.50	0.075	2.50	0.050	Low density mod height shrubs foliage from ground some gaps between
Landscaped Mod_n	0.50	0.150	2.50	0.075	Mod density mod height shrubs foliage from ground few gaps between
Landscaped High_n	0.50	0.200	2.50	0.100	High density mod height shrubs foliage from ground continuous barrier
Sealed Surf Low_n	0.05	0.030	0.25	0.020	roads/parking areas - mostly free of parked vehicles
Sealed Surf Mod_n	0.05	0.030	0.25	0.035	roads/parking areas - significant number of parked vehicles present
Gravel Surf Mod_n	0.15	0.050	0.75	0.035	roads/parking areas - roads with side veg swales - few parked vehicles
Road With Barrier	0.70	0.030	3.50	0.020	paved road with armco style barrier perp to flow - mostly free parked cars
Road With Barrier	1.00	0.050	5.00	0.030	paved road with Armco style barrier perp to flow - significant parked cars at kerb
Res Low_n	0.30	0.100	1.50	0.050	low density typically large blocks with small dwelling footprint significant grassed yard and open fences
Res Mod_n	0.90	0.200	4.50	0.100	average density some solid fences
Res High_n	0.90	0.500	4.50	0.200	typically smaller blocks with large dwelling footprint small yards and frequent solid fences
ResYard High_n	0.90	0.200	4.50	0.150	where dwelling is modelled as a solid - mostly solid fences perpendicular to flow
ResYard Mod_n	0.90	0.150	4.50	0.100	where dwelling is modelled as a solid - some solid fences perpendicular to flow
ResYard Low_n	0.30	0.100	1.50	0.040	where dwelling is modelled as solid - yard mostly free of solid fencing perpendicular to flow
Res Subdivision	0.20	0.070	1.00	0.050	Subdivision under construction
Comm Low_n	0.30	0.250	1.50	0.100	small building footprint significant paving mostly permeable fences
Comm Mod_n	1.00	0.500	5.00	0.250	40% footprint some paving and solid fences

Comm High_n	1.00	0.500	5.00	0.500	80% footprint mostly solid fences
CommYard High_n	0.90	0.200	4.50	0.150	where building is modelled as solid - Stored matl/cars and mostly solid fences perp to flow
CommYard Low_n	0.30	0.100	1.50	0.040	where building is modelled as solid - mostly free of solid fences and stored matl/cars
lightInd Low_n	0.30	0.075	5.00	0.050	low density small building footprint significant paving and permeable fences
LightInd Mod_n	1.00	0.350	5.00	0.100	average density 30% footprint some solid fences
LightInd High_n	1.00	0.350	5.00	0.150	high density 60% footprint some solid fences
LightIndYard High_n	1.00	0.200	5.00	0.150	where building is modelled as solid - mostly paved significant stored matl/car/trucks with solid fences perp to flow
LightIndYard Mod_n	0.30	0.150	1.50	0.075	where building is modelled as solid - mostly paved free of stored matl some cars/trucks with mostly open fences perp to flow
LightIndYard Low_n	0.30	0.100	1.50	0.035	where building is modelled as solid - mostly paved free of stored matl few cars/trucks with open fences perp to flow
ConcChannel	0.02	0.020	0.10	0.011	concrete lined channel
Estuary	0.05	0.035	0.25	0.013	flat variable grade sandy bed low undulations no instream vegetation - typically estuary and/or lake
Creek Low_n	0.30	0.050	1.50	0.035	uniform bed grade and section little instream vegetation
Creek Mod_n	0.50	0.100	2.50	0.075	variable bed grade and section moderate instream vegetation
Creek High_n	1.00	0.150	5.00	0.010	variable bed grade and section substantial instream vegetation (overgrown)
SurfFlowpath	0.30	0.350	1.50	0.150	ill-defined surface flowpath thru otherwise residential area
StructInvert	0.30	0.050	1.50	0.030	waterway with structure over generally clear of vegetation and flat
Wetland Low_n	0.50	0.050	2.50	0.035	some reeds but relatively free of plants with rigid stems
Wetland High_n	1.00	0.100	5.00	0.050	substantial reed growth including plants with rigid stems
RailReserve Low_n	0.05	0.050	0.25	0.040	small relative footprint some paving and open fences
RailReserve High_n	0.50	0.100	2.50	0.070	grassed well maintained light occasional shrub only
RoadReserve	0.15	0.100	0.75	0.050	irregularly mown or grazed grassland with some paving (footpaths) and shrubs
SolidBuildings	1.00	10.000	5.00	10.000	nom 1% permeability modelled as n =100*0.100

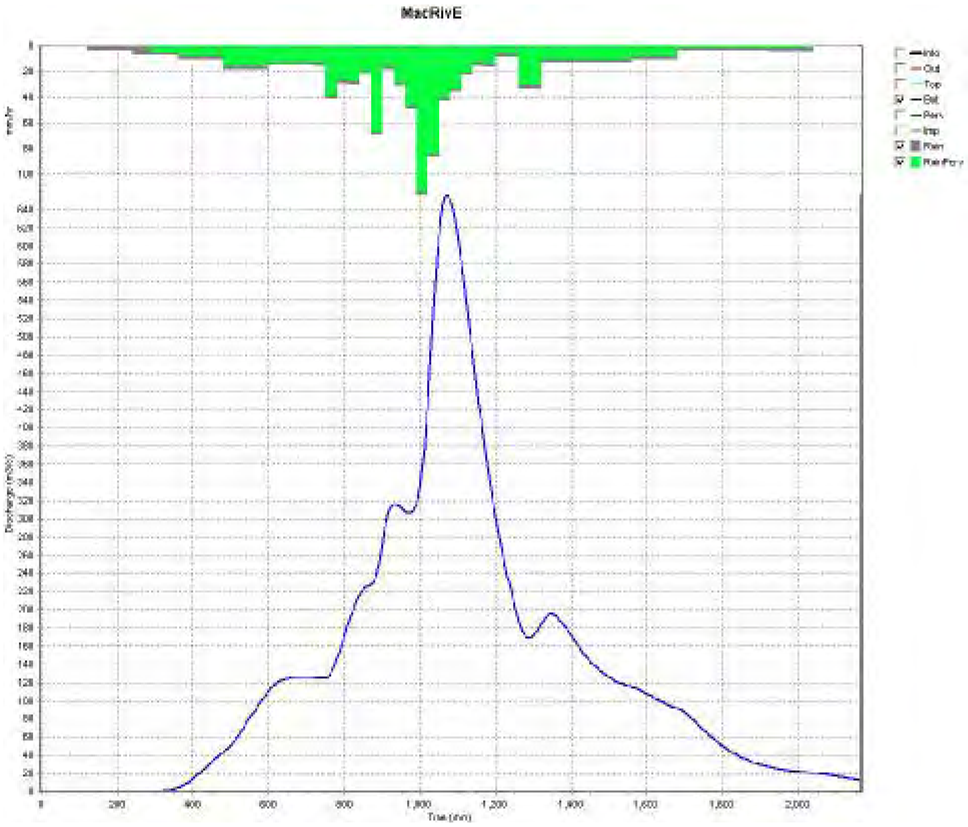
APPENDIX E5: ADOPTED SURFACE ROUGHNESS VALUES

DESIGN FLOOD HYDROLOGY

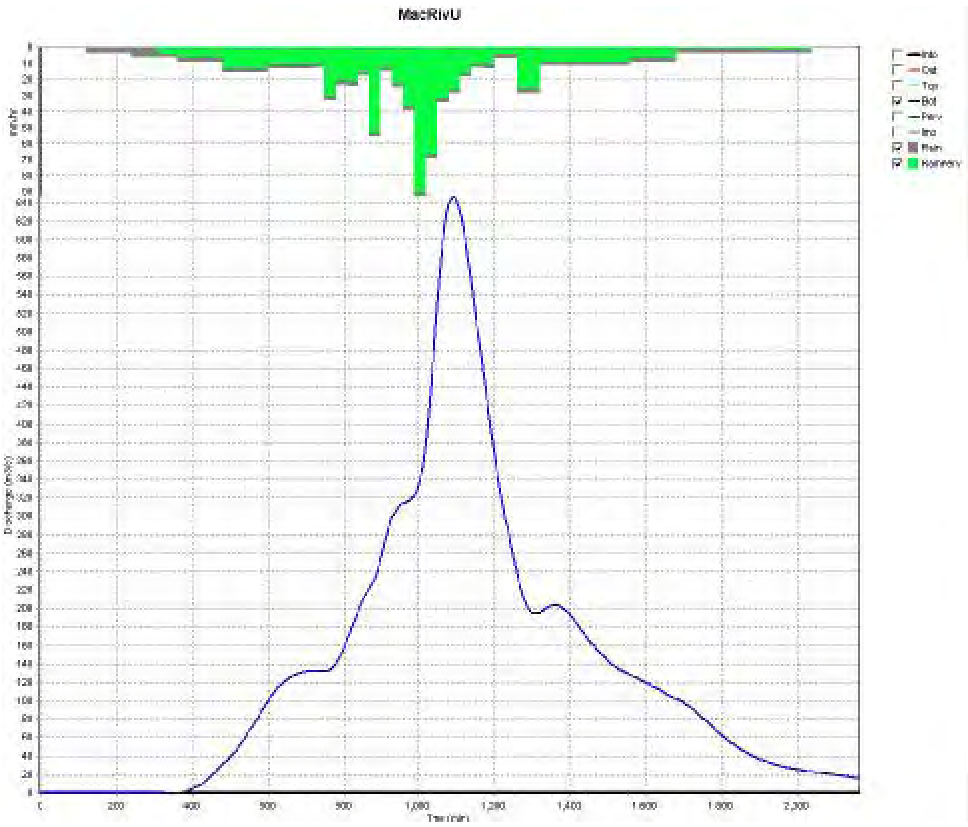
F.1 **Hydrographs at Locations of Interest – 1%AEP**
F.2 **Hydrographs at Locations of Interest - PMF**

F
F
F
F

APPENDIX F

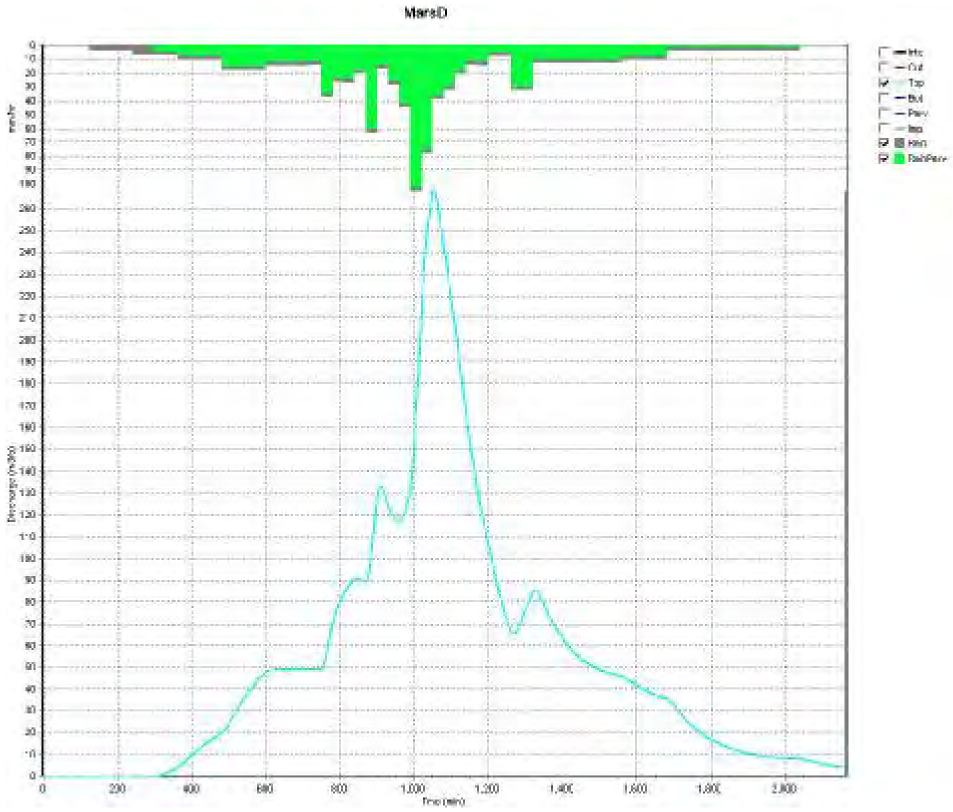


1% AEP HYDROGRAPH in MACQUARIE RIVULET at SUNNYBANK GAUGE

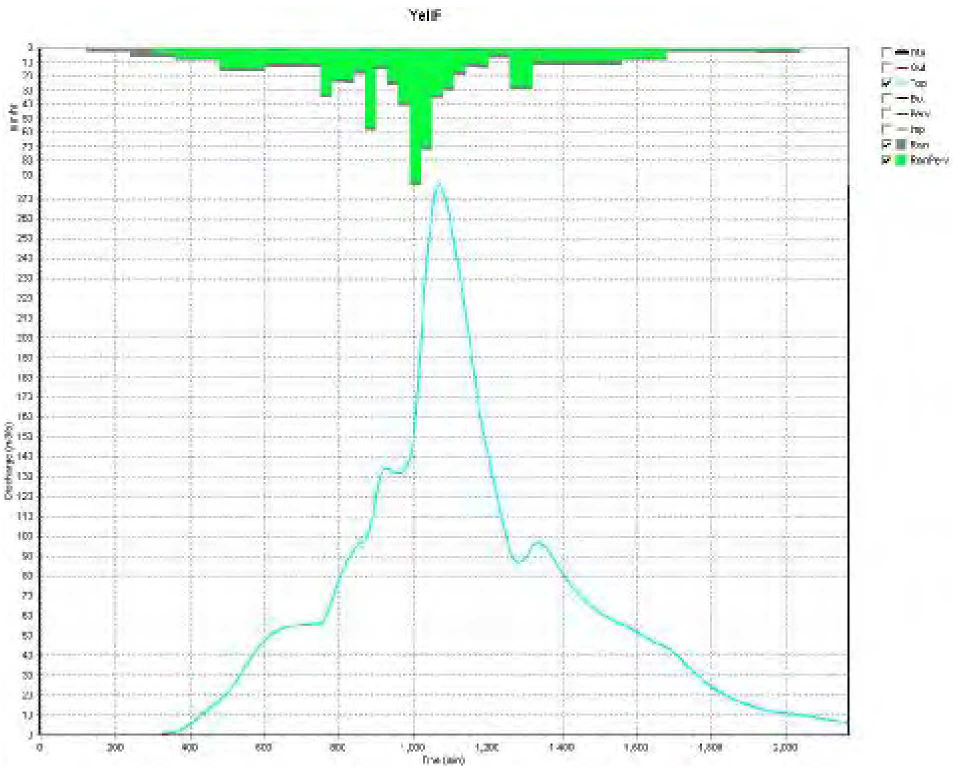


1% AEP HYDROGRAPH IN MACQUARIE RIVULET at MANSONS BRIDGE

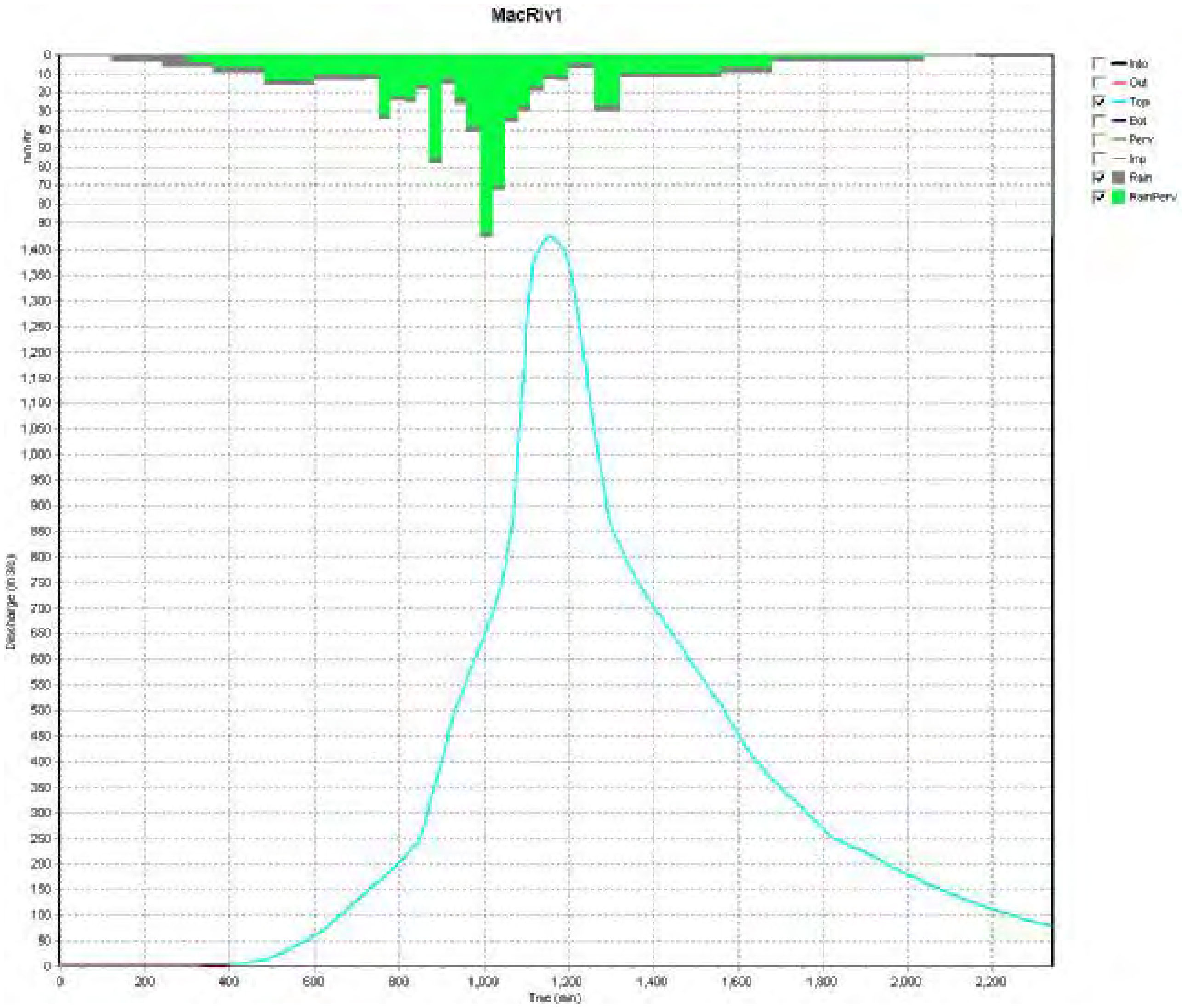
APPENDIX F1: HYDROGRAPHS AT LOCATIONS OF INTEREST – 1% AEP



1% AEP HYDROGRAPH IN MARSHALL MT CK AT MARSHALL MT RD

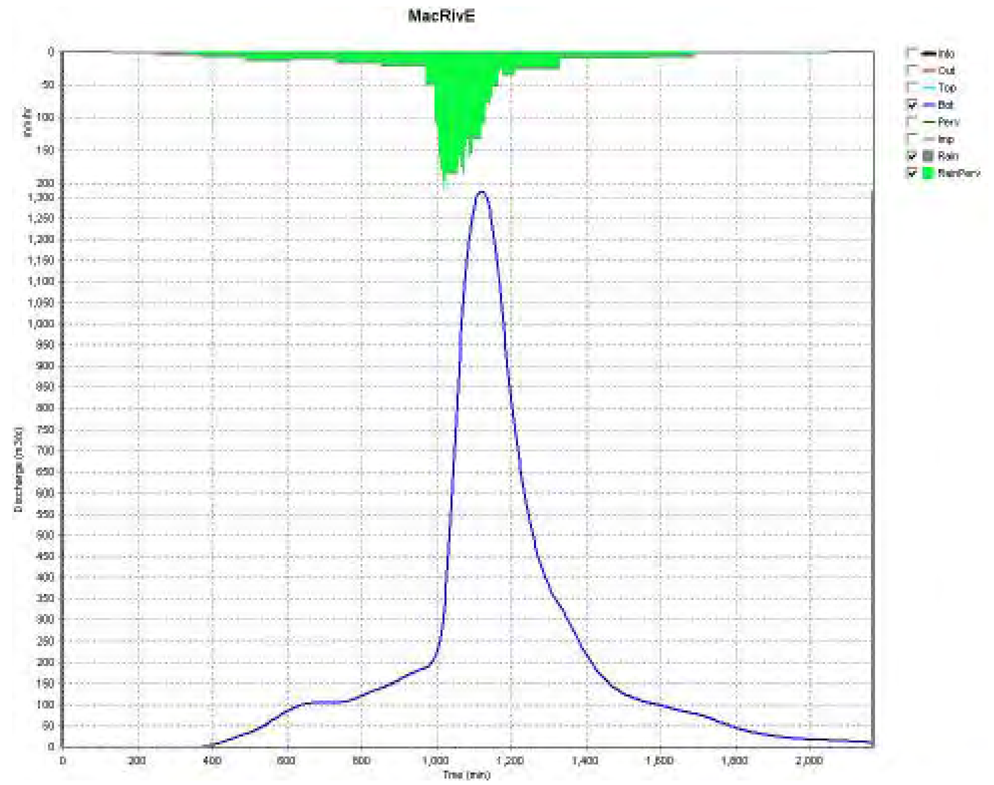


1% AEP HYDROGRAPH IN YELLOWROCK CK AT ILLAWARRA HWAY

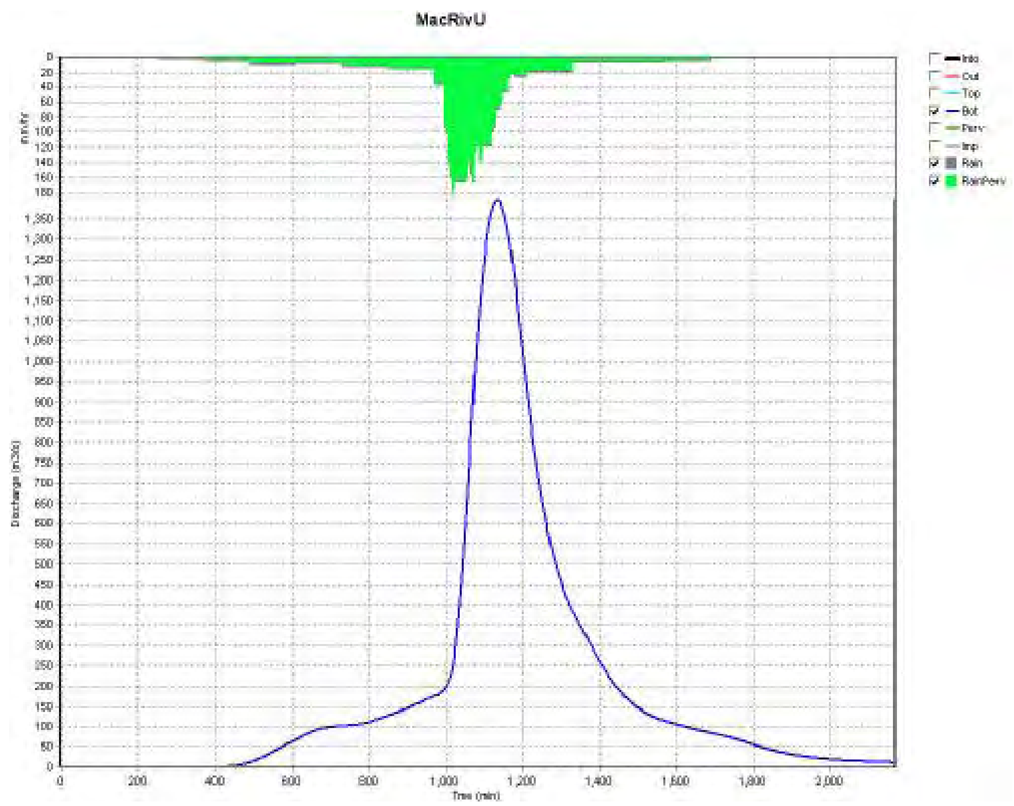


1% AEP HYDROGRAPH IN MACQUARIE RIVULET AT PHWAY GAUGE

APPENDIX F1: HYDROGRAPHS AT LOCATIONS OF INTEREST – 1% AEP (ctd)

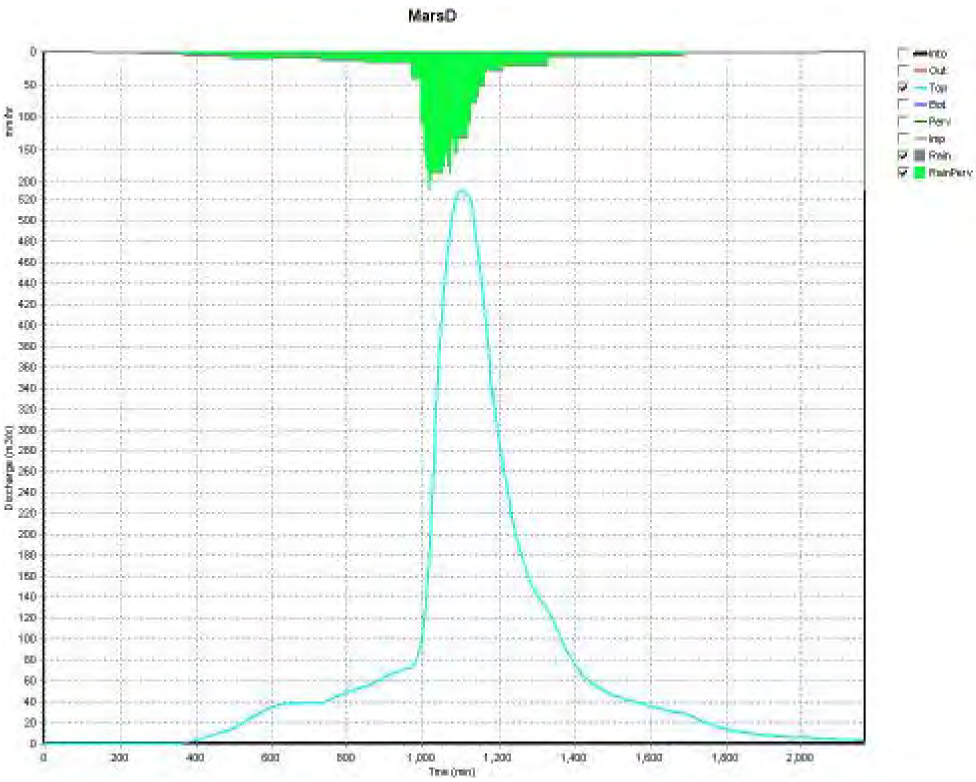


PMF HYDROGRAPH IN MACQUARIE RIVULET AT SUNNY BANK GAUGE

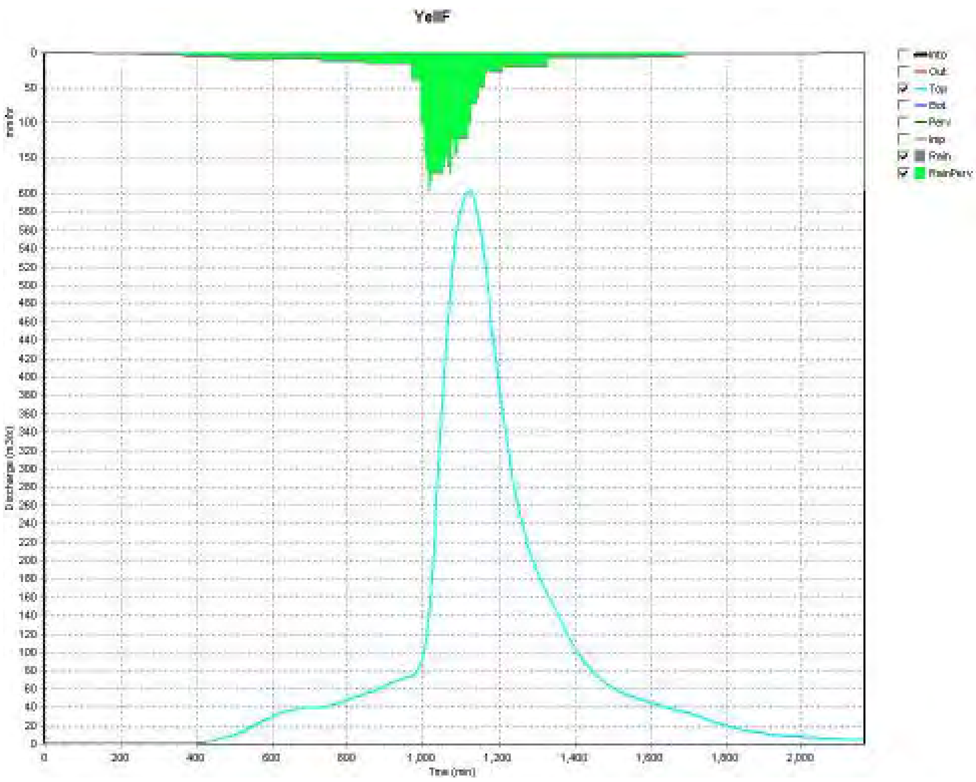


PMF HYDROGRAPH IN MACQUARIE RIVULET AT MANSONS BRIDGE

APPENDIX F2: HYDROGRAPHS AT LOCATIONS OF INTEREST – PMF

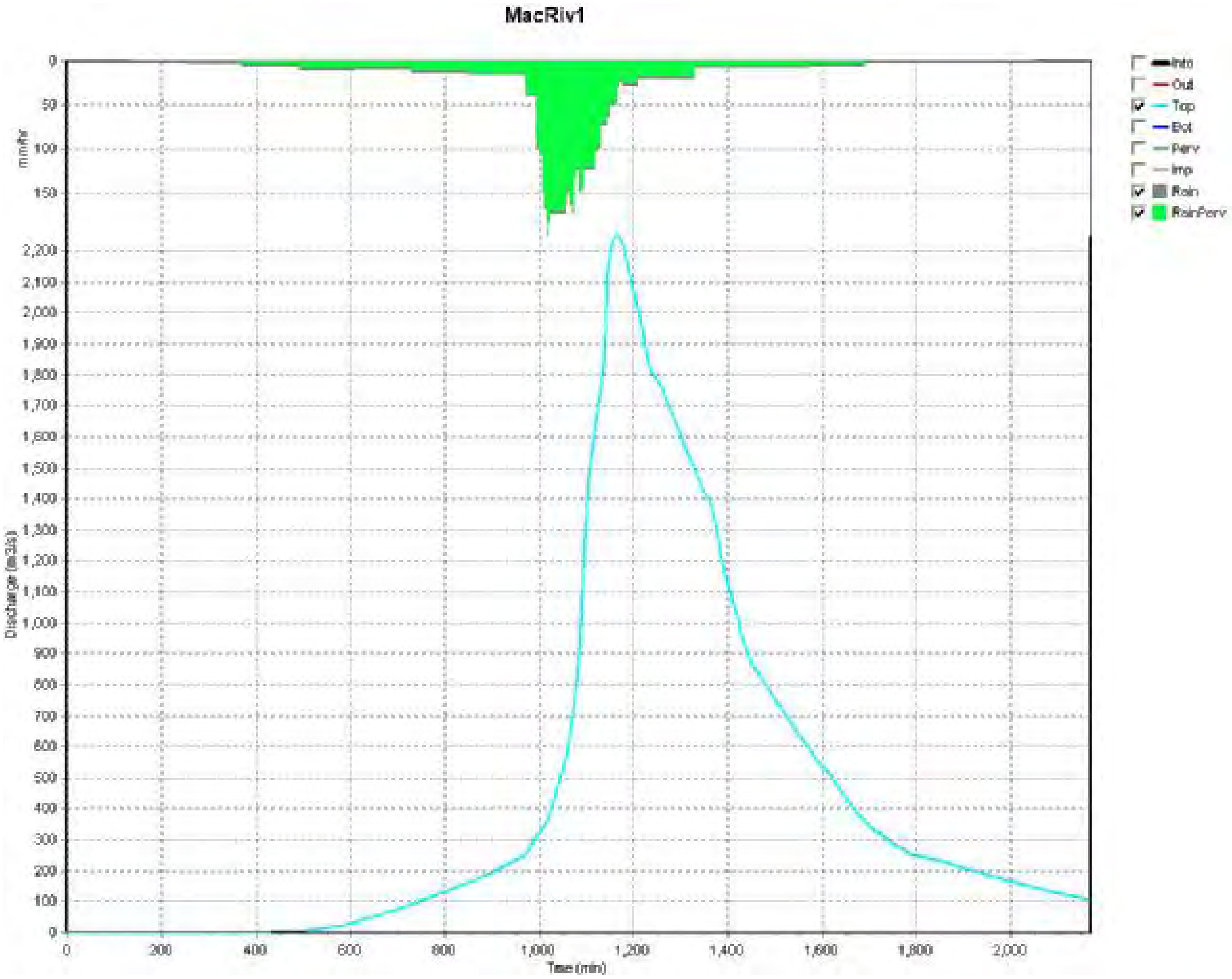


PMF HYDROGRAPH IN MARSHALL MT CK AT MARSHALL MT RD



PMF HYDROGRAPH IN YELLOWROCK CK ILLAWARRA HWAY

APPENDIX F2: HYDROGRAPHS AT LOCATIONS OF INTEREST – PMF (ctd)



PMF HYDROGRAPH IN MACQUARIE RIVULET AT PHWAY GAUGE

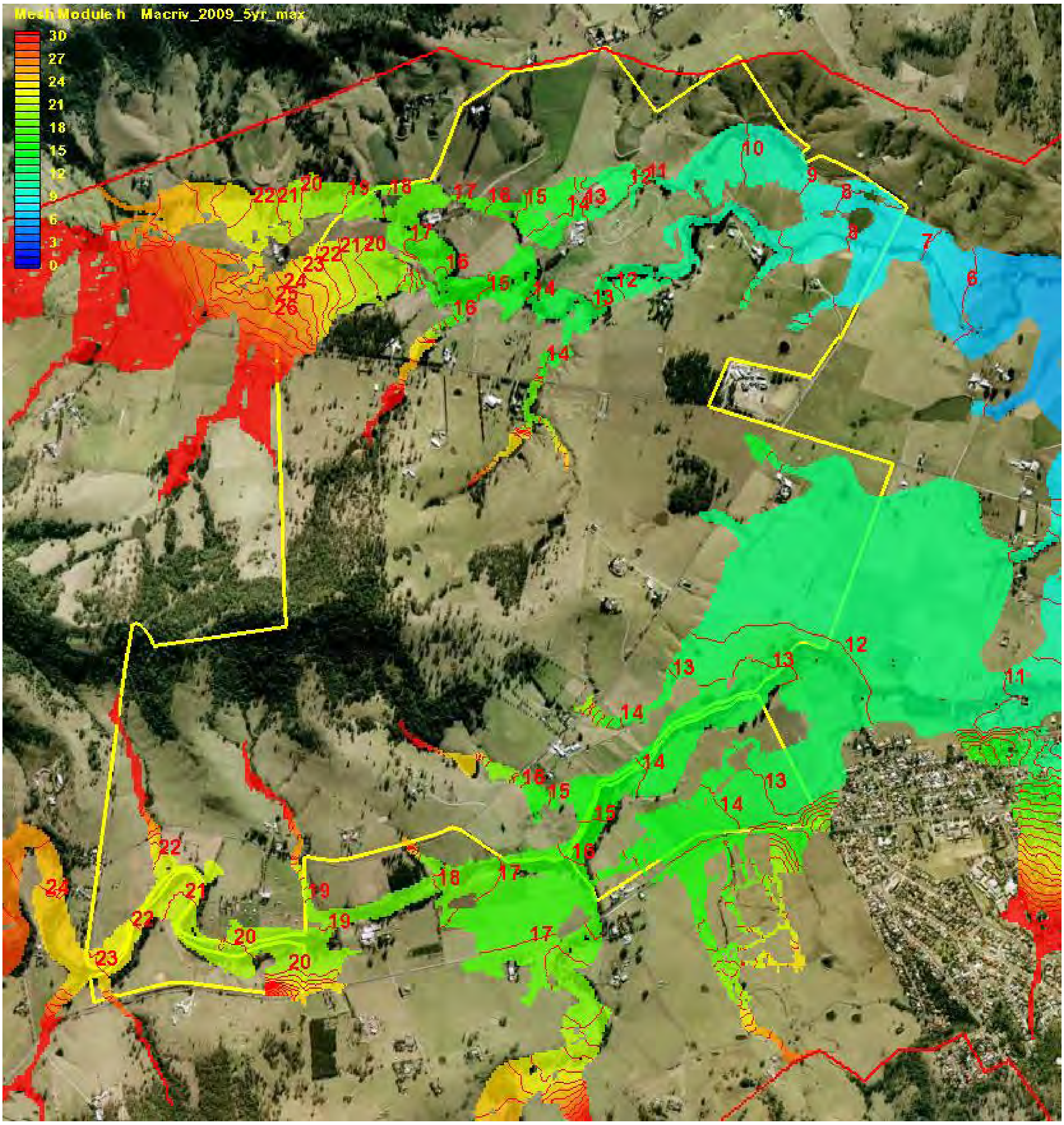
APPENDIX F2: HYDROGRAPHS AT LOCATIONS OF INTEREST – PMF(ctd)

DESIGN FLOOD HYDRAULICS

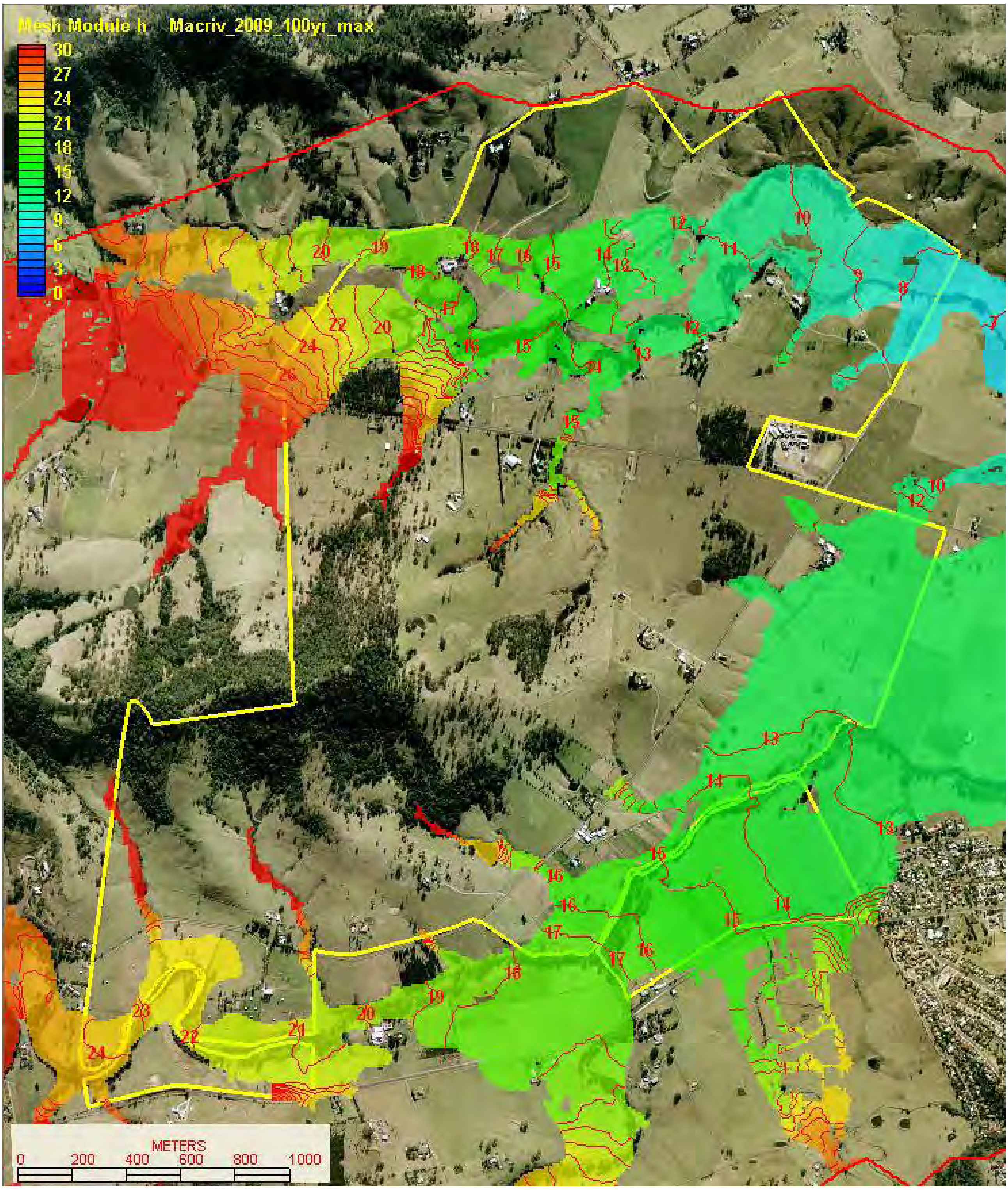
G 1 **20% AEP Peak Elevation Flood Surface**
G 2 **1% AEP Peak Elevation Flood Surface**
G.3 **PMF Peak Elevation Flood Surface**
G 4 **20% Peak Velocity Flood Surface**
G.5 **1% Peak Velocity Flood Surface**
G.6 **PMF Peak Velocity Flood Surface**
G.7 **20% Peak Depth Flood Surface**
G.8 **1% Peak Depth Flood Surface**
G.9 **PMF Peak Depth Flood Surface**
G.10 **20% Peak VxD Flood Surface**
G.11 **1% Peak VxD Flood Surface**
G.12 **PMF Peak VxD Flood Surface**
G.13 **20% Prov Hyd Hazard Flood Surface**
G.14 **1% Prov Hyd Hazard Flood Surface**
G.15 **PMF Prov Hyd Hazard Flood Surface**

G
G
G
G

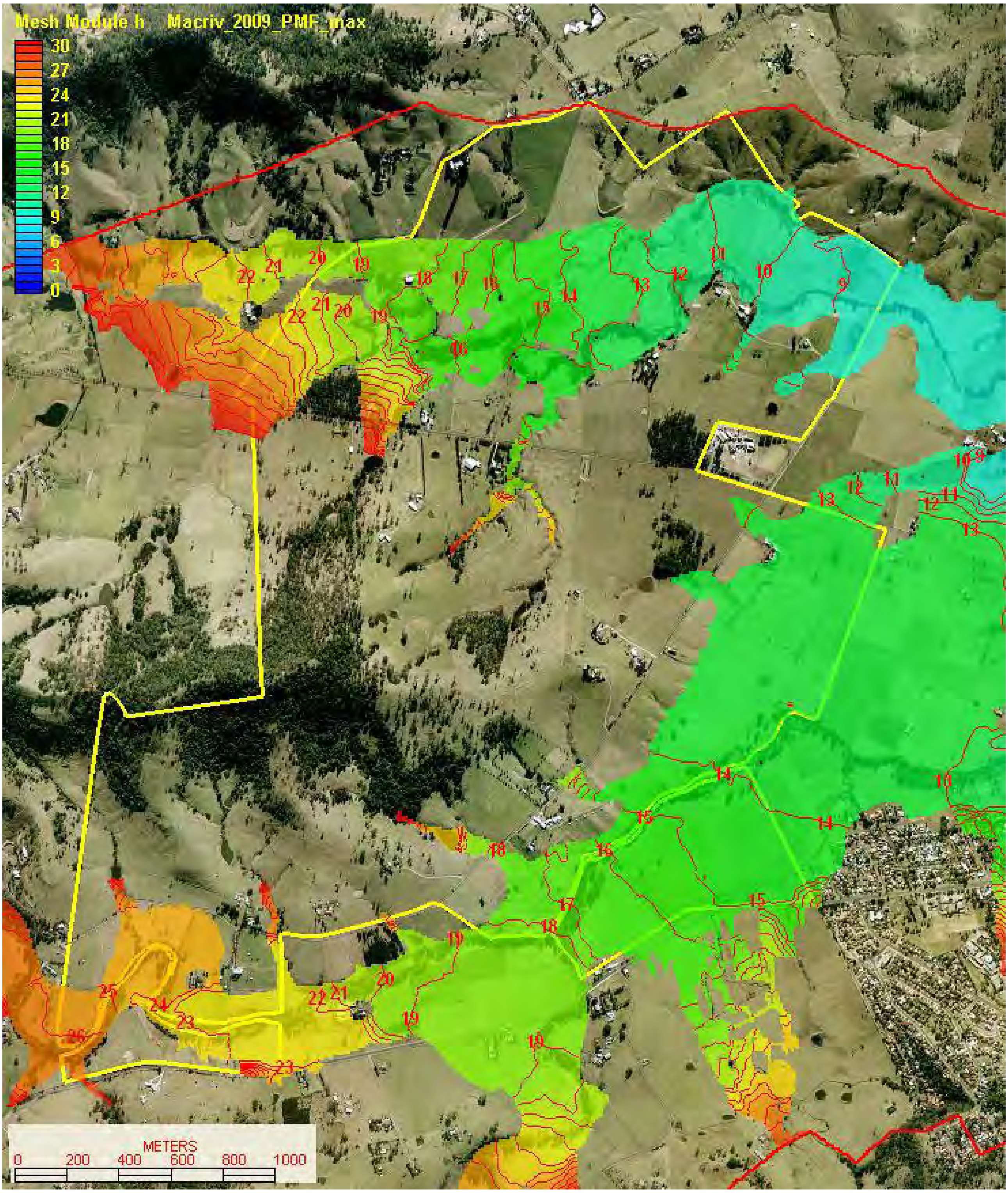
APPENDIX G



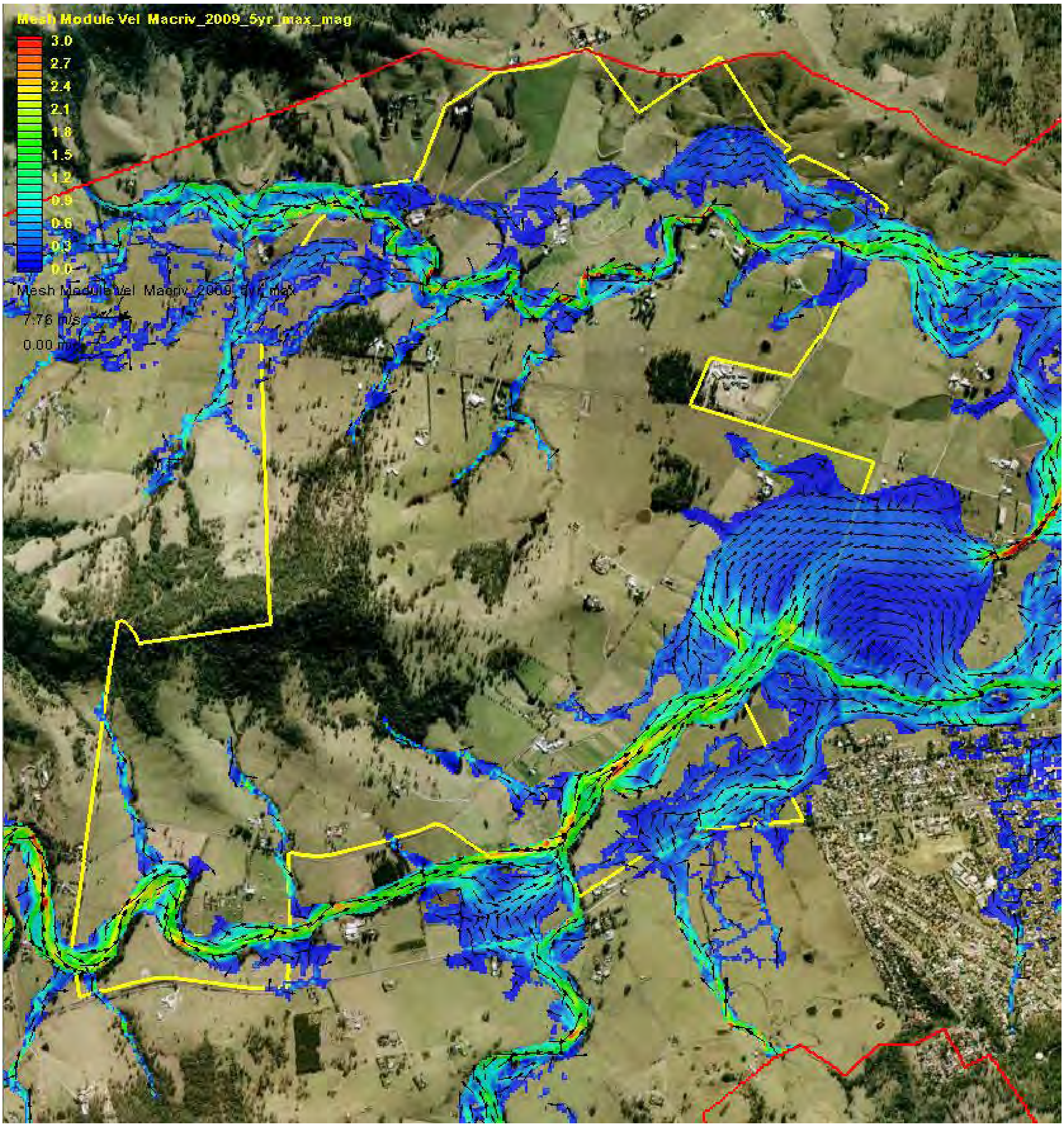
APPENDIX G.1: 20% AEP Peak Elevation Flood Surface



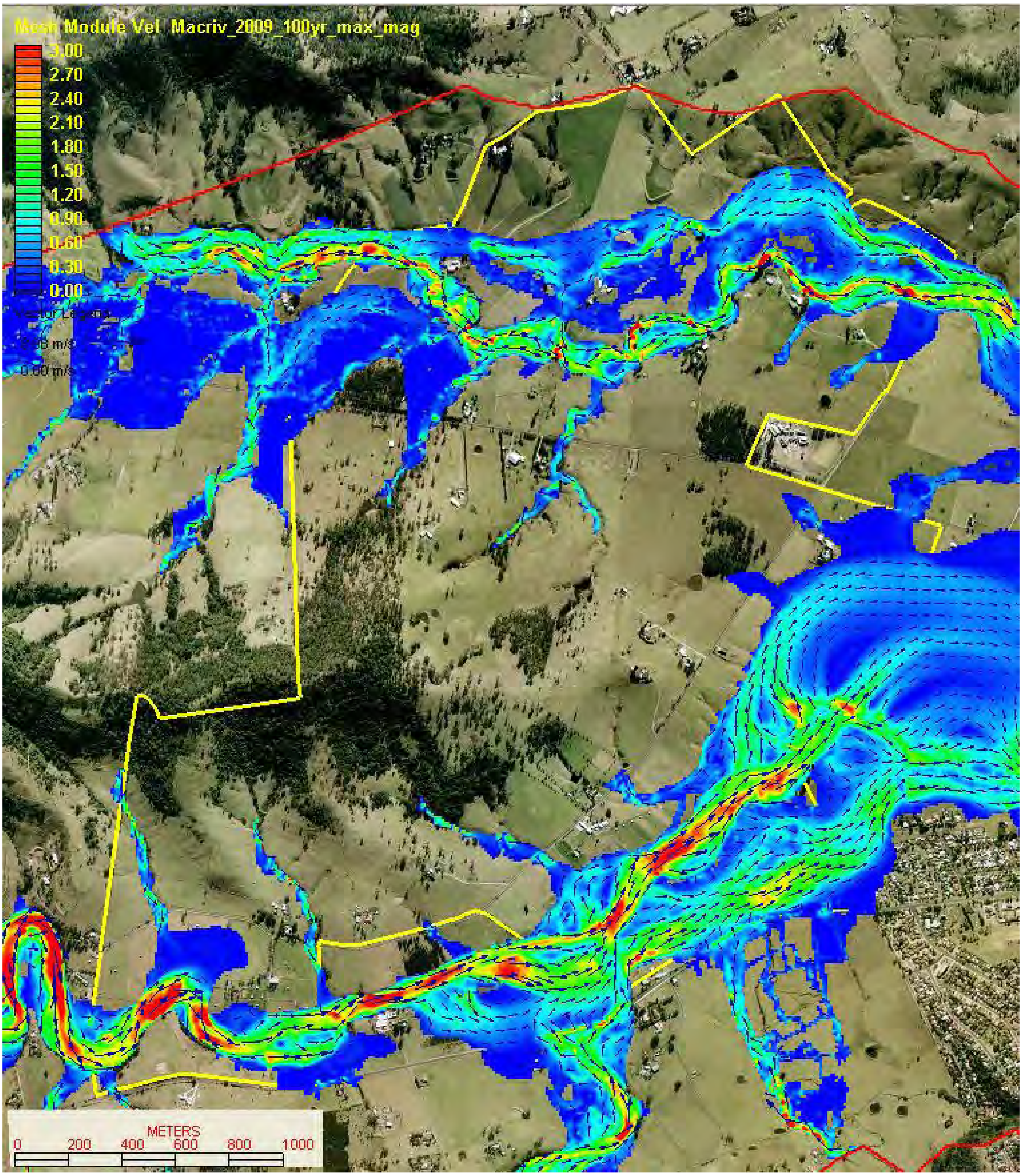
APPENDIX G.2: 1% AEP Peak Elevation Flood Surface



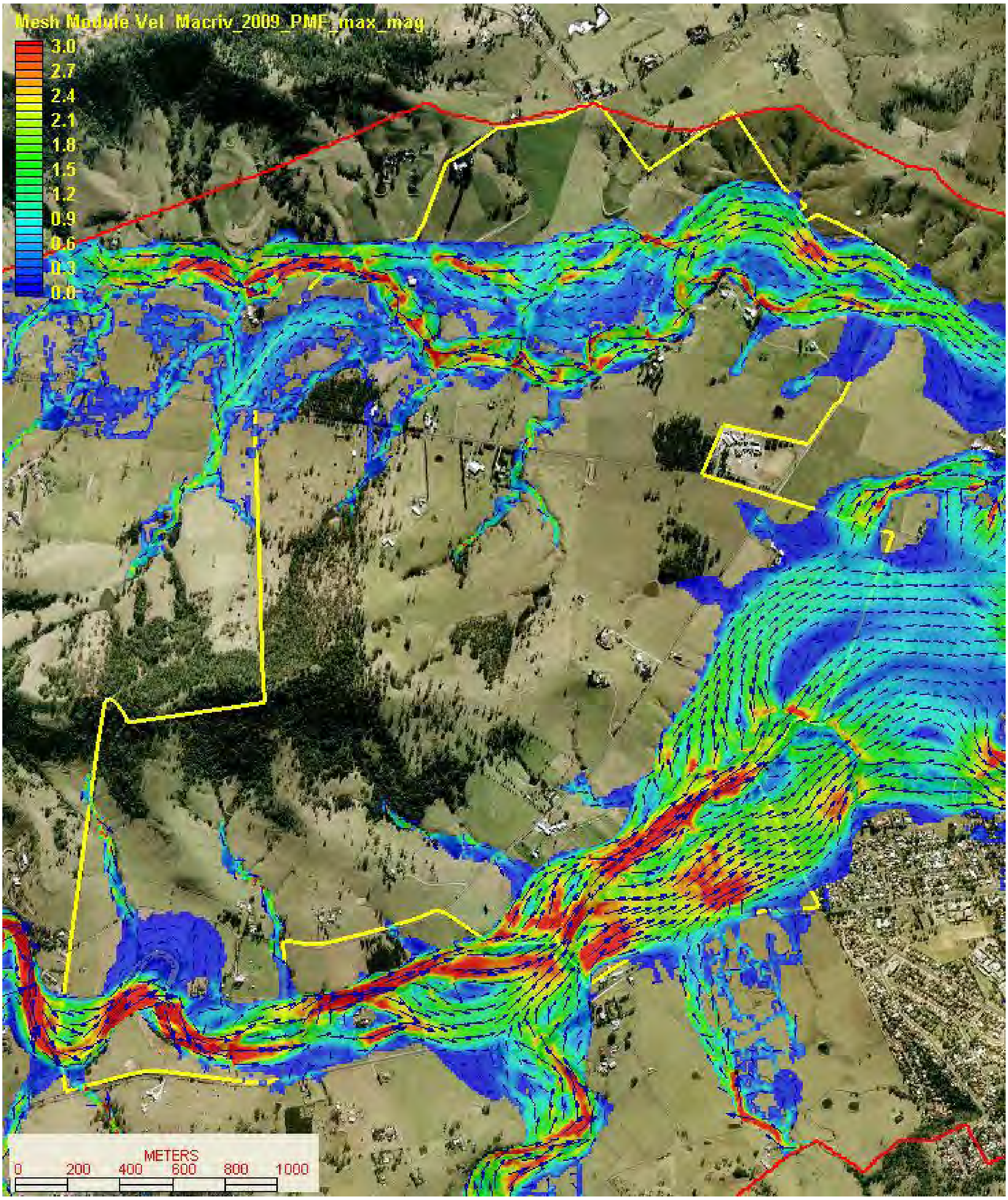
APPENDIX G.3: PMF Peak Elevation Flood Surface



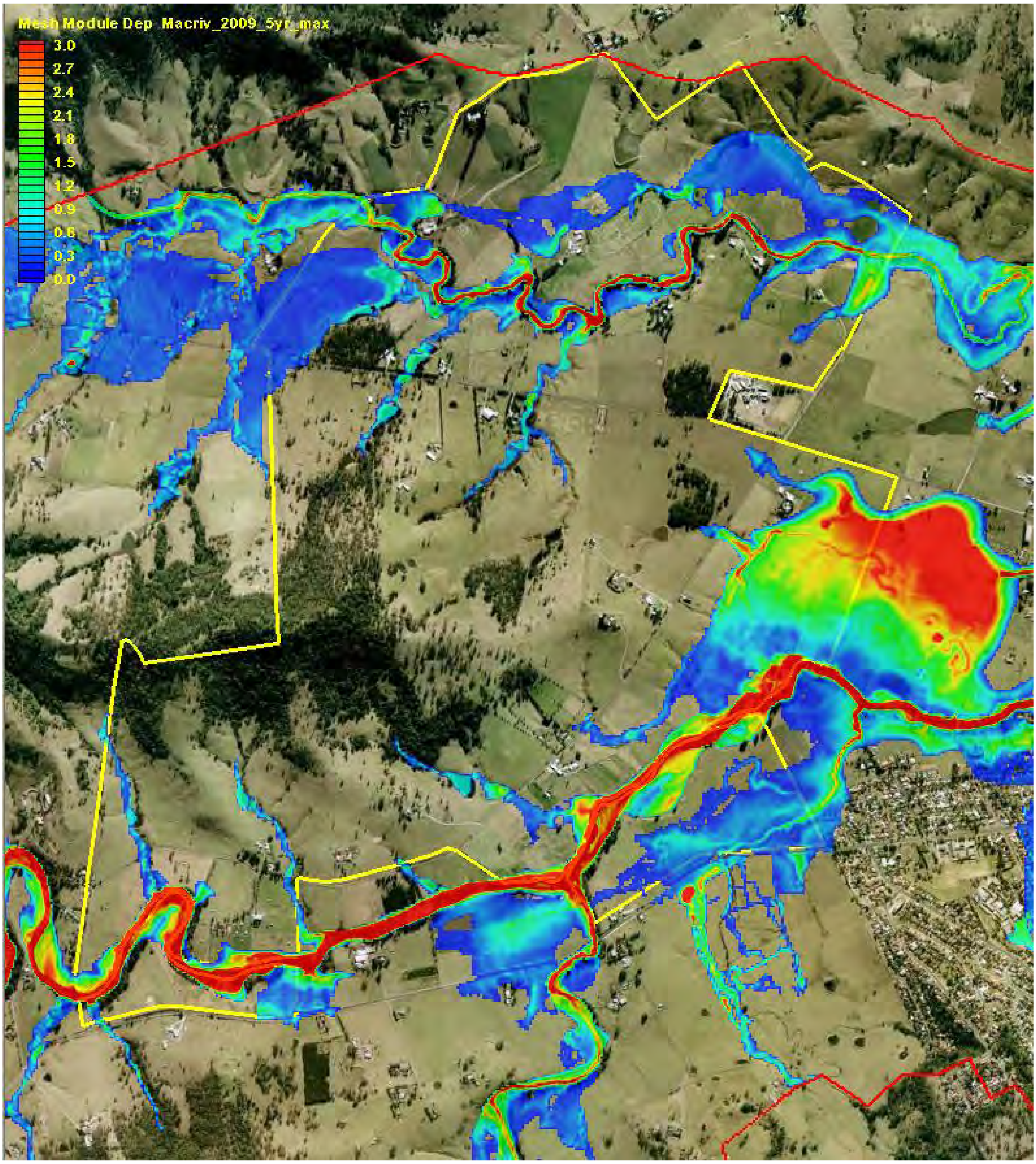
APPENDIX G.4: 20% Peak Velocity Flood Surface



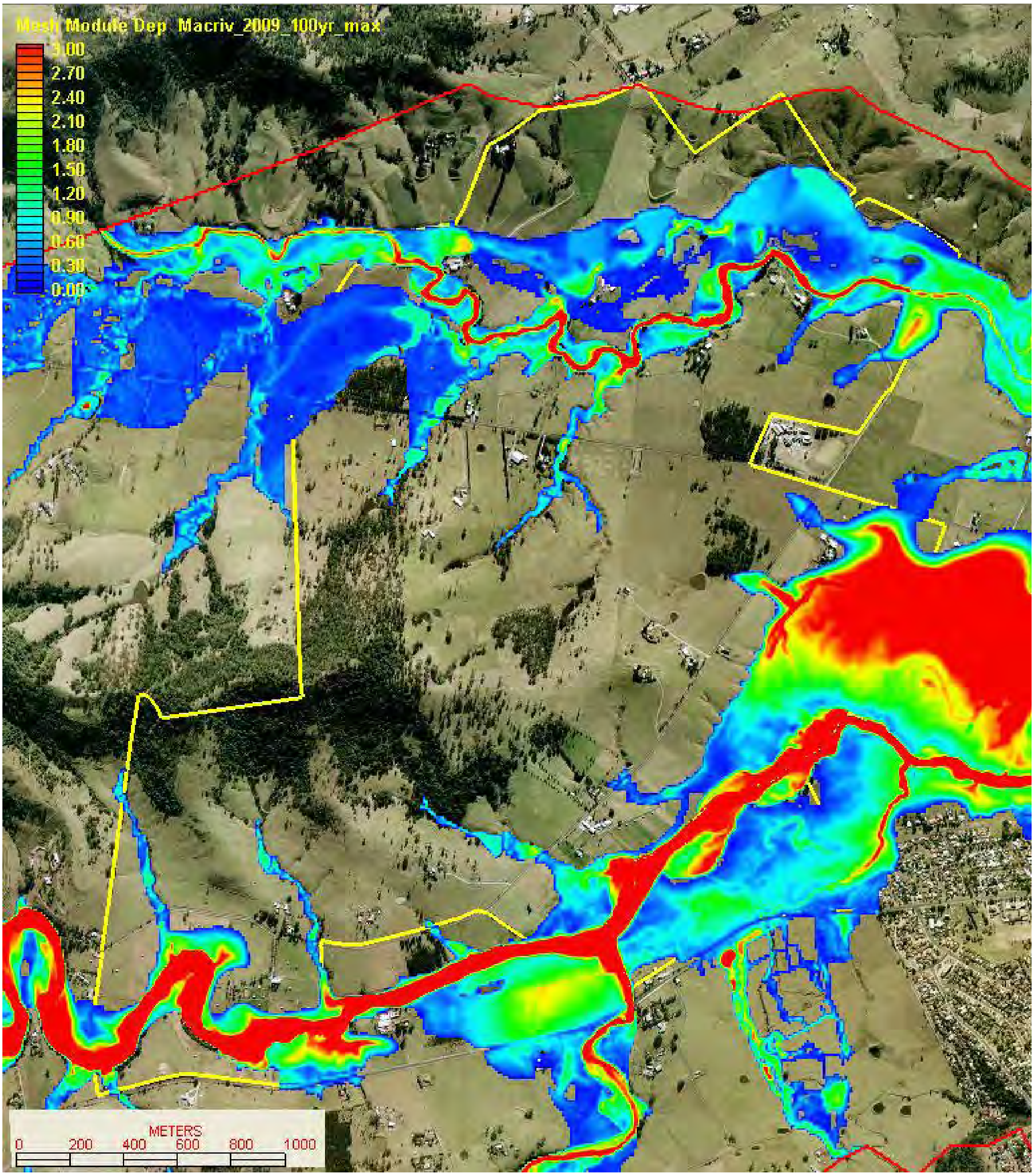
APPENDIX G.5: 1% Peak Velocity Flood Surface



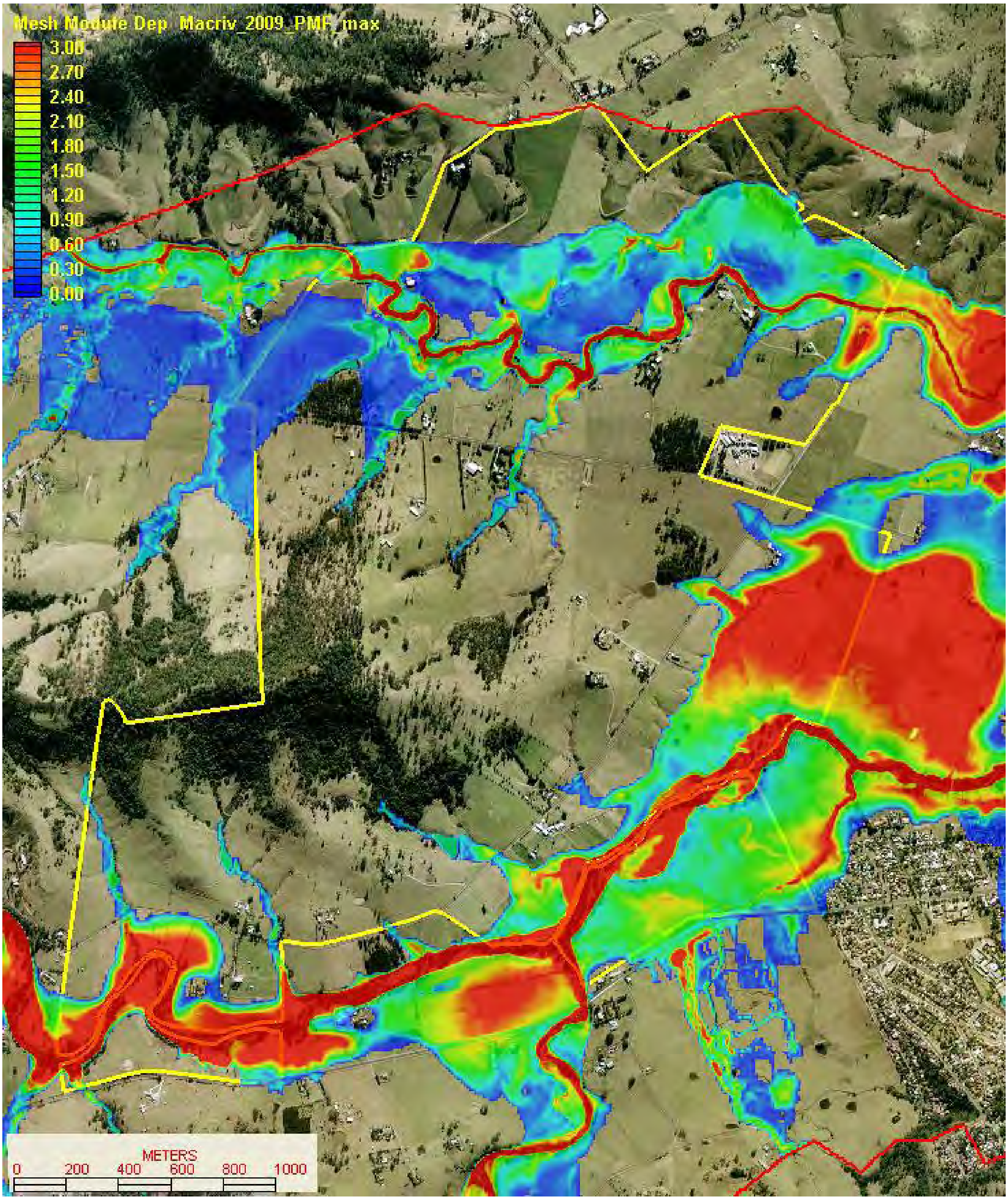
APPENDIX G.6: PMF Peak Velocity Flood Surface



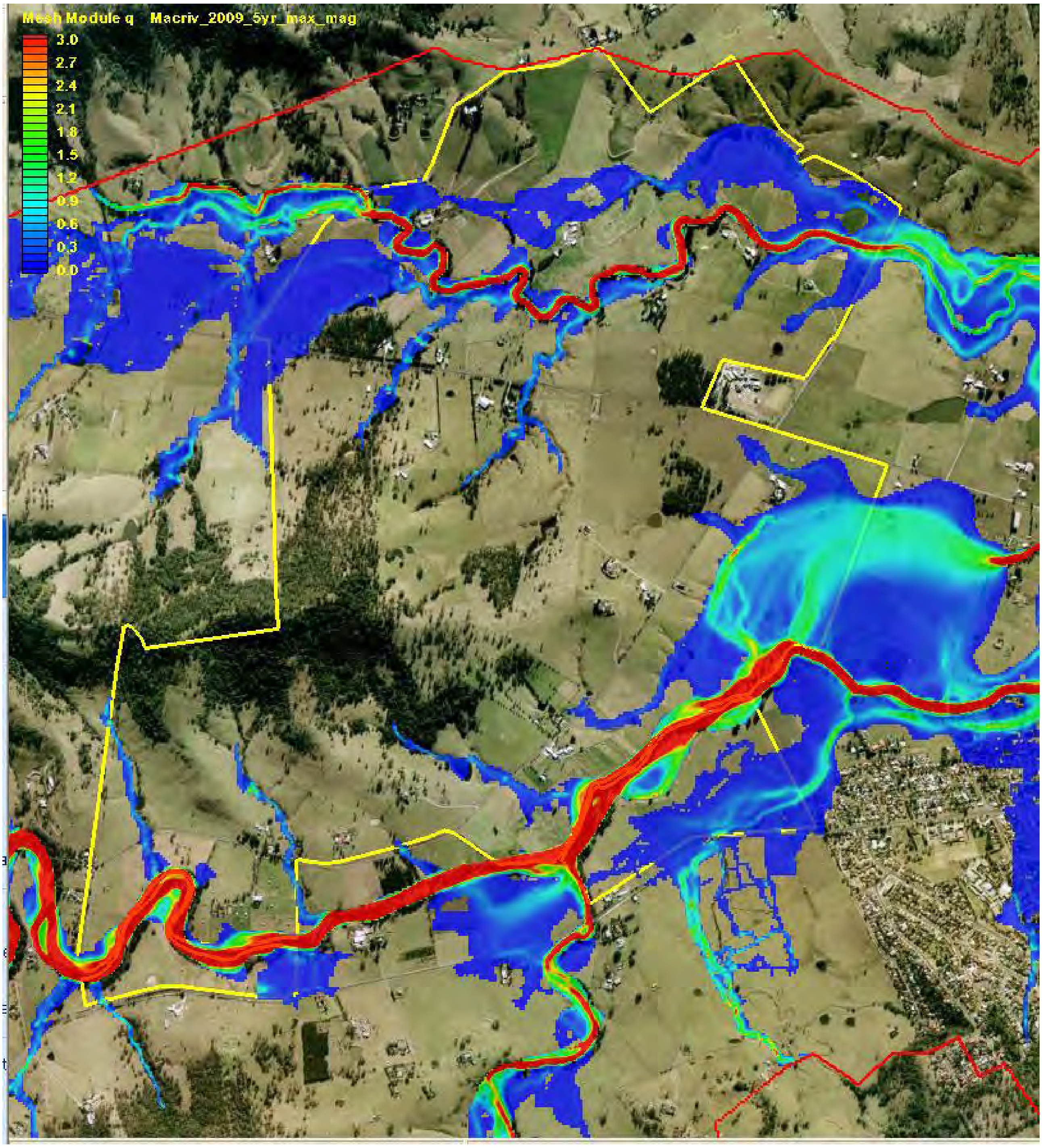
APPENDIX G.7: 20% Peak Depth Flood Surface



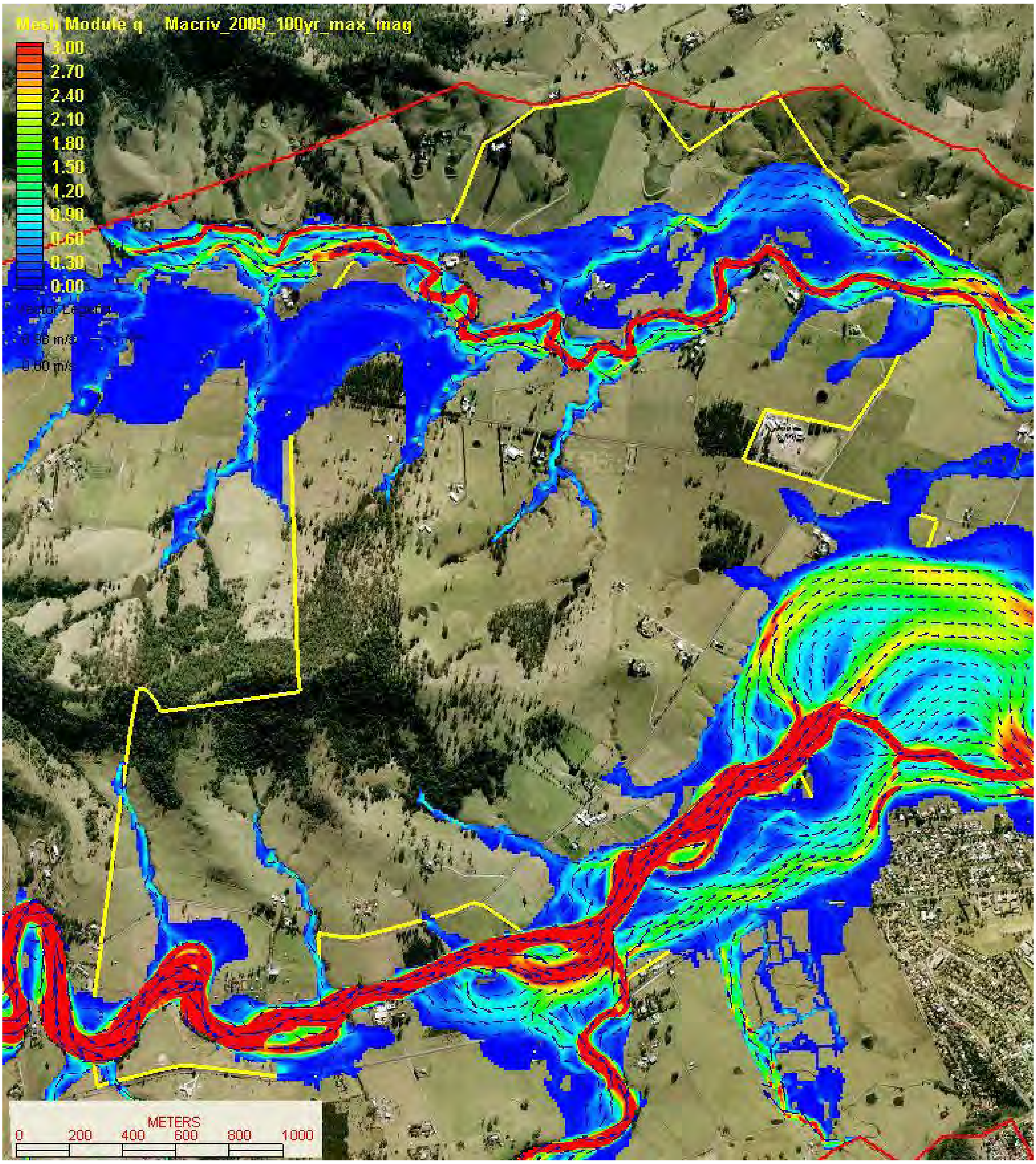
APPENDIX G.8: 1% Peak Depth Flood Surface



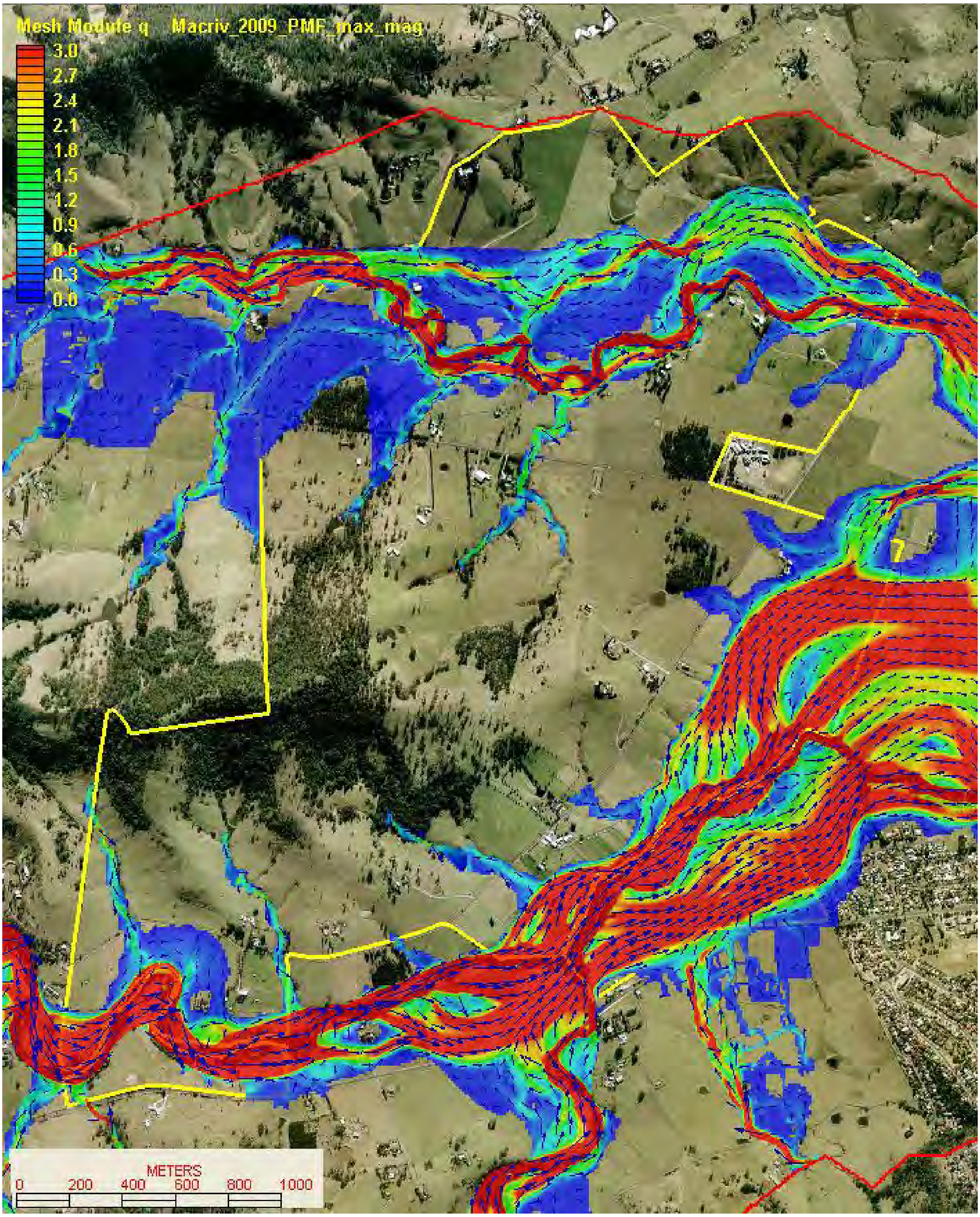
APPENDIX G.9: PMF Peak Depth Flood Surface



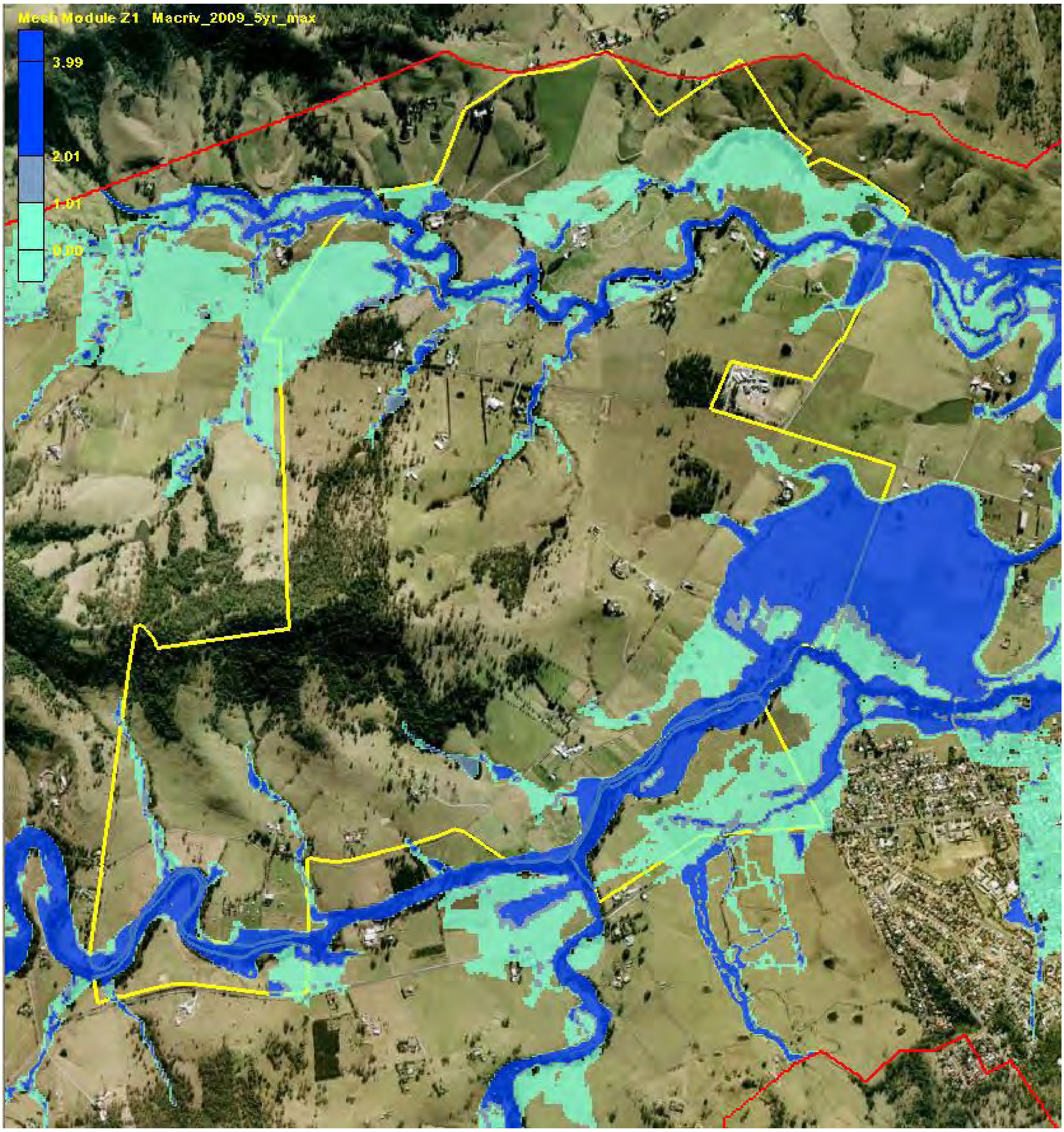
APPENDIX G.10: 20% Peak V*D Flood Surface



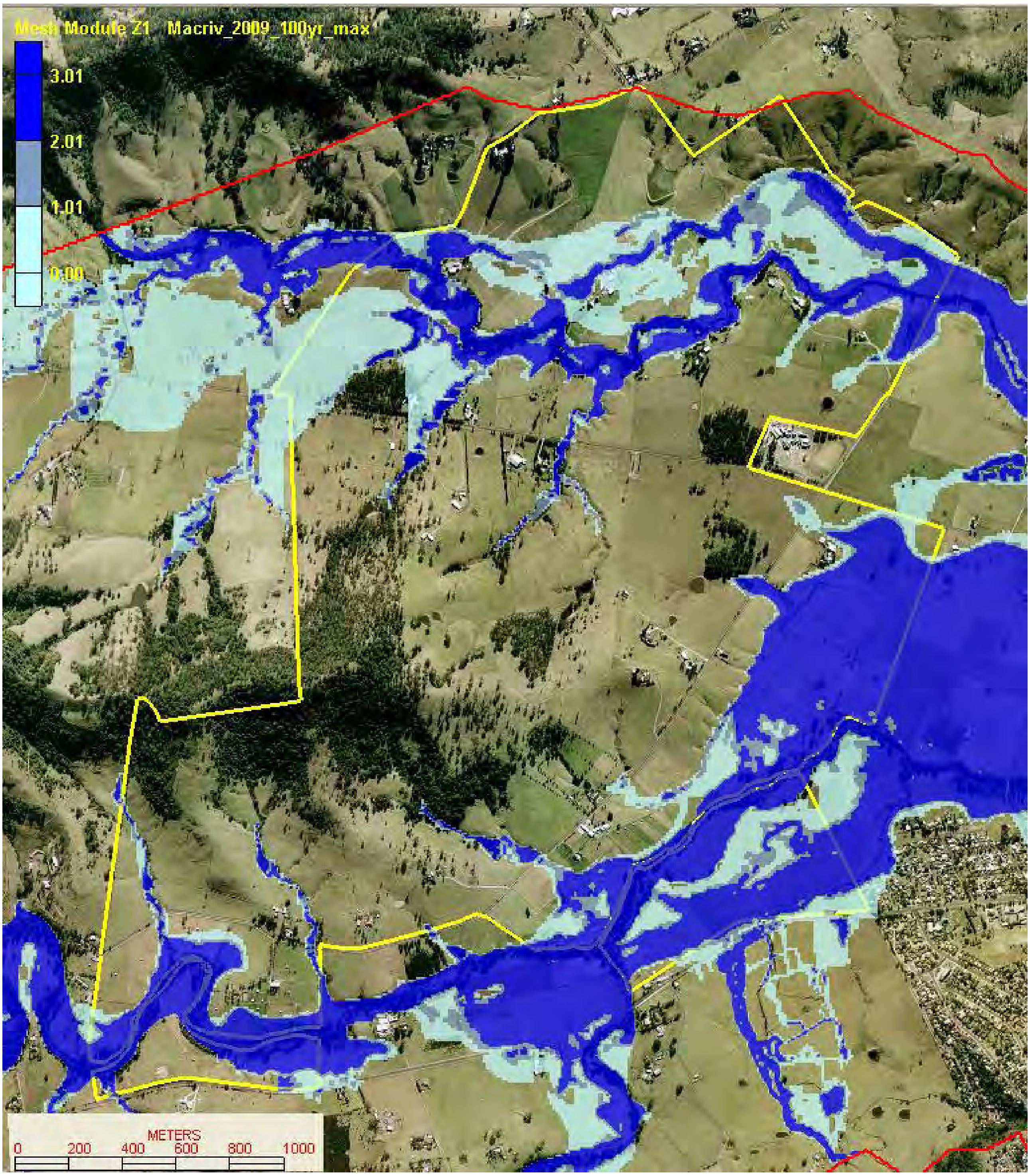
APPENDIX G.11: 1% Peak V*D Flood Surface



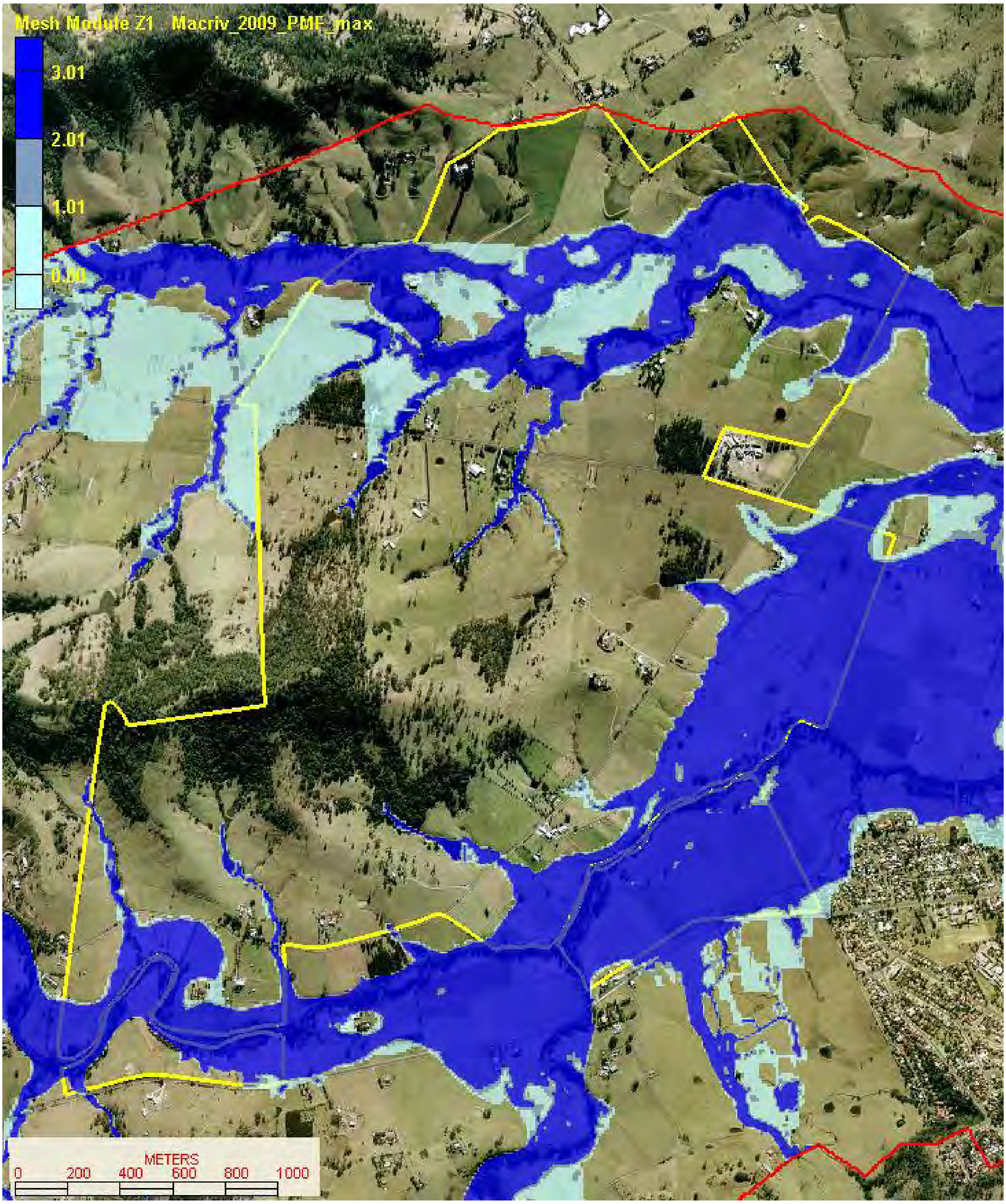
APPENDIX G.12: PMF Peak V*D Flood Surface

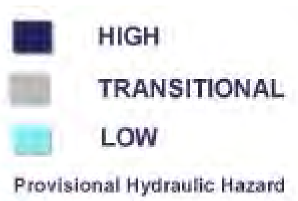


APPENDIX G.13: 20% Provisional Hydraulic Hazard Flood Surface



APPENDIX G.14: 1% Provisional Hydraulic Hazard Flood Surface





APPENDIX G.15: PMF Provisional Hydraulic Hazard Flood Surface