SHOALHAVEN CITY COUNCIL

NOWRA AND BROWNS CREEKS FLOOD STUDY

Issue No. 4
MARCH 2005

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Document Amendment and Approval Record

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1	Draft Report - Issue for Review	CRT / DJT (*12/5/03*)		
2	Final Draft Report incorporating additional hydraulic modelling	CRT / DJT (*12/03/04*)		
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FOREWORD

The primary objective of the NSW Government's *Flood Prone Land Policy* is to reduce the impact of flooding and flood liability on individual owners and occupiers of flood prone property, and to reduce private and public losses resulting from floods, utilising ecologically positive methods wherever possible.

It is therefore directed toward providing solutions to existing flooding problems in developed areas and ensuring that new development is compatible with the flood hazard and does not create additional flooding problems in other areas. Policy and practice are outlined in the NSW Government publication titled, *'Floodplain Management Manual: the management of flood liable land'* (*2001*).

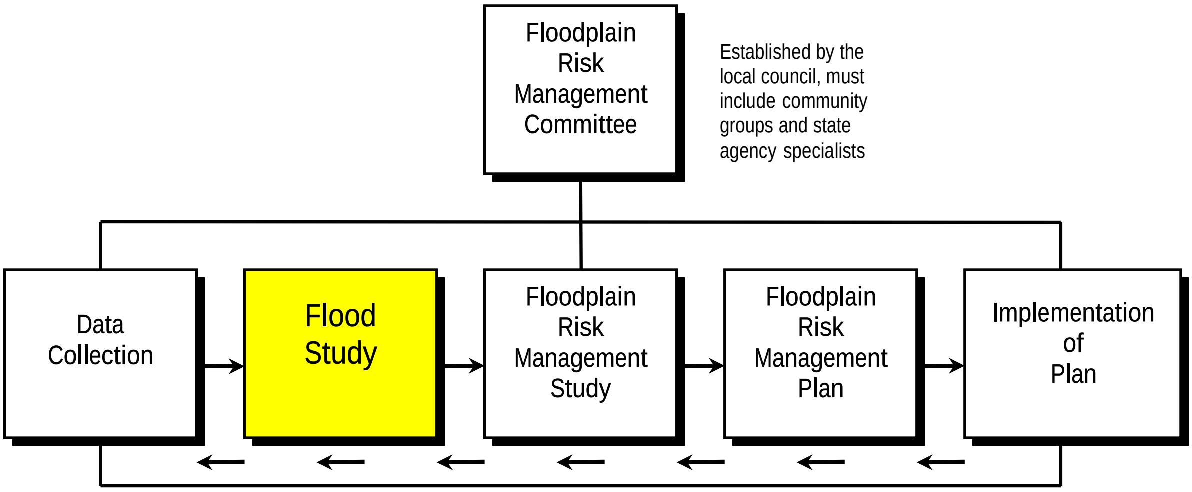
Under the Policy, the management of flood liable land remains the responsibility of local government. The NSW Government provides financial and specialist technical assistance to local government in the discharge of their floodplain risk management responsibilities.

A detailed description of the inter-relationship between the six iterative stages of floodplain risk management under the NSW Government's Flood Prone Land Policy is provided overleaf. This flow chart also shows the link between the various outcomes of the studies involved in the floodplain risk management process and the implementation of measures (*both planning and structural*) to reduce flood damages and other negative impacts.

Shoalhaven City Council commenced this process when it formed the Shoalhaven Floodplain Management Committee. Council and the Committee, with the technical and financial support of the NSW Department of Infrastructure, Planning & Natural Resources (*DIPNR*), have proceeded with the floodplain management process by commissioning this Flood Study.

The *'Nowra and Browns Creeks Flood Study'* represents the third of the six stages. It has been prepared to assist Shoalhaven City Council and the local community to understand the existing flood behaviour along Nowra and Browns Creeks. It defines key flood characteristics such as predicted peak flood level and flow velocity, and provisional flood hazard.

The information contained in the report will be used in the subsequent floodplain risk management study as the basis for assessing potential floodplain risk management measures that could be incorporated into the floodplain risk management plan for implementation to reduce existing flood damages and manage future development consistent with the identified flood risks and hazards.



Compilation of existing data and collection of additional data. Usually undertaken by consultants appointed by the council.

Defines the nature and extent of the flood problem, in technical rather than map form. Usually undertaken by consultants appointed by the council.

Determines options in consideration of social, ecological and economic factors relating to flood risk. Usually undertaken by consultants appointed by the council.

Preferred options publicly exhibited and subject to revision in light of responses. Formally approved by the council after public exhibition and any necessary revisions due to public comments.

Flood, response and property modification measures including mitigation works, planning controls, flood warnings, flood readiness and response plans, environmental rehabilitation, ongoing data collection and monitoring.

FLOODPLAIN RISK MANAGEMENT PROCESS

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GLOSSARY

annual exceedance probability (AEP)	The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (*that is a one-in-twenty chance*) of a peak flood discharge of 500 m^3/s or larger occurring in any one year (*see average recurrence interval*).
Australia Height Datum (AHD)	A common national surface level datum corresponding approximately to mean sea level.
average recurrence interval (ARI)	The long term average number of years between the occurrence of a flood as big as, or larger than, the selected event. For example, floods with a discharge as great as, or greater than, the 20 year ARI flood event will occur on average once every 20 years. The ARI is another way of expressing the likelihood of occurrence of a flood event.
catchment	The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
design flood	A hypothetical flood representing a specific likelihood of occurrence (*for example the 100 year ARI or 1% annual exceedance probability flood*). The design flood may comprise two or more single source dominated floods.
development	Is defined in Part 4 of the Environmental Planning and Assessment Act (*EP&A Act*). infill development: refers to development of vacant blocks of land that are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development. new development: refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power. redevelopment: refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services.

discharge	The rate of flow of water measured in terms of volume per unit time, for example cubic metres per second (*m^3/s*). Discharge is different from the speed or velocity of flow which is a measure of how fast the water is moving for example, metres per second (*m/s*).
effective warning time	The time available after receiving advice of an impending flood and before floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.
flash flooding	Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within 6 hours of the causative rainfall.
flood	Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a water course, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami.
flood behaviour	The pattern/characteristics/nature of a flood. The flood behaviour is often presented in terms of the peak average velocity of floodwaters and the peak water level at a particular location.
flood awareness	An appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.
flood frequency analysis	A statistical analysis of historical flood records to determine estimates of the magnitude of floods of a selected probability of exceedance (*as adapted from AR&R 1998*)
flood fringe areas	The remaining area of flood prone land after floodway and flood storage areas have been defined.
flood hazard	See hazard
flood level	The height or elevation of flood waters relative to a datum (*typically the Australian Height Datum*). Also referred to as “stage”.
floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
flood planning levels (FPLs)	The combinations of flood levels and freeboards selected for planning purposes, as determined in floodplain risk management studies and incorporated in floodplain risk management plans. The of FPL’s supersedes the “standard flood event” referred to in the 1986 edition of the *‘Floodplain Development Manual’*.

flood proofing	A combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to reduce or eliminate flood damages.
floodplain management	The coordinated management of the risks associated with human activities that occur on the floodplain.
flood prone land	Land susceptible to flooding by the probable maximum flood (PMF) event. Flood prone land is synonymous with flood liable land.
flood risk	Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk can be divided into three types, existing, future and continuing risk. They are described below. existing flood risk: the risk a community is exposed to as a result of its location on the floodplain. future flood risk: the risk a community may be exposed to as a result of new development on the floodplain. continuing flood risk: the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.
flood storage areas	Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storages can increase the severity of flood impacts by reducing natural flood attenuation. Hence it is necessary to investigate a range of flood sizes before defining flood storage areas.
floodway areas	Those areas of the floodplain where a significant discharge of water occurs during floods. They are areas often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flow, or a significant increase in flood levels.
freeboard	A factor of safety typically used in relation to the setting of floor levels and levee crest levels etc. It is usually expressed as the difference in height between the adopted flood planning level and the flood used to determine the flood planning level. Freeboard provides a factor of safety to compensate for uncertainties in the estimation of flood levels across the floodplain, such as wave action, localised hydraulic behaviour and impacts that are specific event related such as levee and embankment settlement, and other effects such as “greenhouse” and climate change. Freeboard is included in the flood planning level.

hazard	A source of potential harm or a situation with a potential to cause loss. In relation to this study the hazard is flooding which has the potential to cause damage to the community. Definitions of high and low hazard categories are provided in Appendix G of the *Floodplain Management Manual* (*2001*).
historical flood	A flood which has actually occurred.
hydraulics	The term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.
hydrograph	A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood.
hydrology	The term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.
local overland flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
mainstream flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.
mathematical / computer models	The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.
minor, moderate and major flooding	Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood. <u>minor flooding</u>: Causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded. <u>moderate flooding</u>: Low lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered. <u>major flooding</u>: Appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.
peak discharge	The maximum discharge occurring during a flood event.

probable maximum flood (PMF)	The largest flood that could conceivably occur at a particular location, usually estimated from the probable maximum precipitation. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land; that is, the floodplain. The extent, nature and potential consequences of flooding associated with the PMF event should be addressed in a floodplain risk management study.
probable maximum precipitation (PMP)	The greatest depth of precipitation for a given duration that is meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long term climatic trends (*World Meteorological Organisation 1986*). It is the primary input to the estimation of the probable maximum flood.
probability	A statistical measure of the expected chance of flooding (*see annual exceedance probability*).
risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of this flood study (*and the subsequent floodplain risk management study*) it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
runoff	The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.
stage	Equivalent to "water level". Both are measured with reference to a specified datum.
stage hydrograph	A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.
velocity	The speed or rate of motion (*distance per unit of time*) in a specific direction at which the flood waters are moving. Typically, modelled flood velocities in a river or creek are quoted as the depth and width averaged velocity, i.e., the average velocity across the whole river or creek section (*adapted from Chambers English Dictionary 1988*).

1 INTRODUCTION

Nowra is located on the banks of the Shoalhaven River about 160 kilometres south of Sydney. It has a population of about 25000 and has experienced steady growth over the last 10 years.

Nowra Creek is a tributary of the Shoalhaven River that drains the area to the south-west of the central business district and major residential areas of Nowra (*refer* **Figure 1**). It is an ephemeral stream that flows in a northerly direction, joining the Shoalhaven River just upstream of the Princes Highway bridge crossing.

Browns Creek joins Nowra Creek near the intersection of the Princes Highway and Hillcrest Avenue (*refer* **Figure 1**). It drains that section of the catchment that extends to the east of the Princes Highway.

The catchment of Nowra and Browns Creeks has an area of about 20 km^2. The catchment includes the residential areas of western Nowra and the industrial precinct of South Nowra.

Due to the limited flow carrying capacity of the channels of both creek channels, it is not uncommon for floodwaters to 'breakout' and travel overland across their respective floodplains. The Nowra and Browns Creeks catchment has experienced major floods in the past, most notably in 1974, 1978 and 1989. The most recent incidence of flooding occurred in 1999.

When flooding of Nowra and Browns Creeks occurs, many of the roads within the catchment are inundated making them impassable for several hours. This has the potential to isolate residents and workers in the industrial precinct and to cause significant damage to existing infrastructure. As a consequence of these experiences, Council has adopted a policy of restricting development in low lying areas that are potentially vulnerable to flooding.

Flooding of Nowra and Browns Creeks is generally caused by one of several scenarios occurring in isolation or in combination. These scenarios are:

(1) Catchment response to intense rainfall over the local Nowra / Browns Creek catchment, resulting in the concentration of runoff within tributary streams and the "backing-up" of floodwaters where channel constrictions exist (*e.g., Central Avenue culvert crossing*).

(2) Localised concentration of rainfall within the catchment, resulting in localised pondage of runoff due to inadequate drainage systems.

(3) Mainstream flooding of the Shoalhaven River, leading to elevated water levels near the confluence of the Shoalhaven River and Nowra Creek, and the subsequent "backing-up" of floodwaters along the lower reach of Nowra Creek and inundation of the floodplain.

In recognition of this flood history, and to assist in the assessment of future development, Shoalhaven City Council commissioned Patterson Britton & Partners to undertake a Flood Study for Nowra and Browns Creeks. This report documents the findings of the Flood Study, which extends from Central Avenue and Warra Warra Road within the South Nowra Industrial Area to the Shoalhaven River.

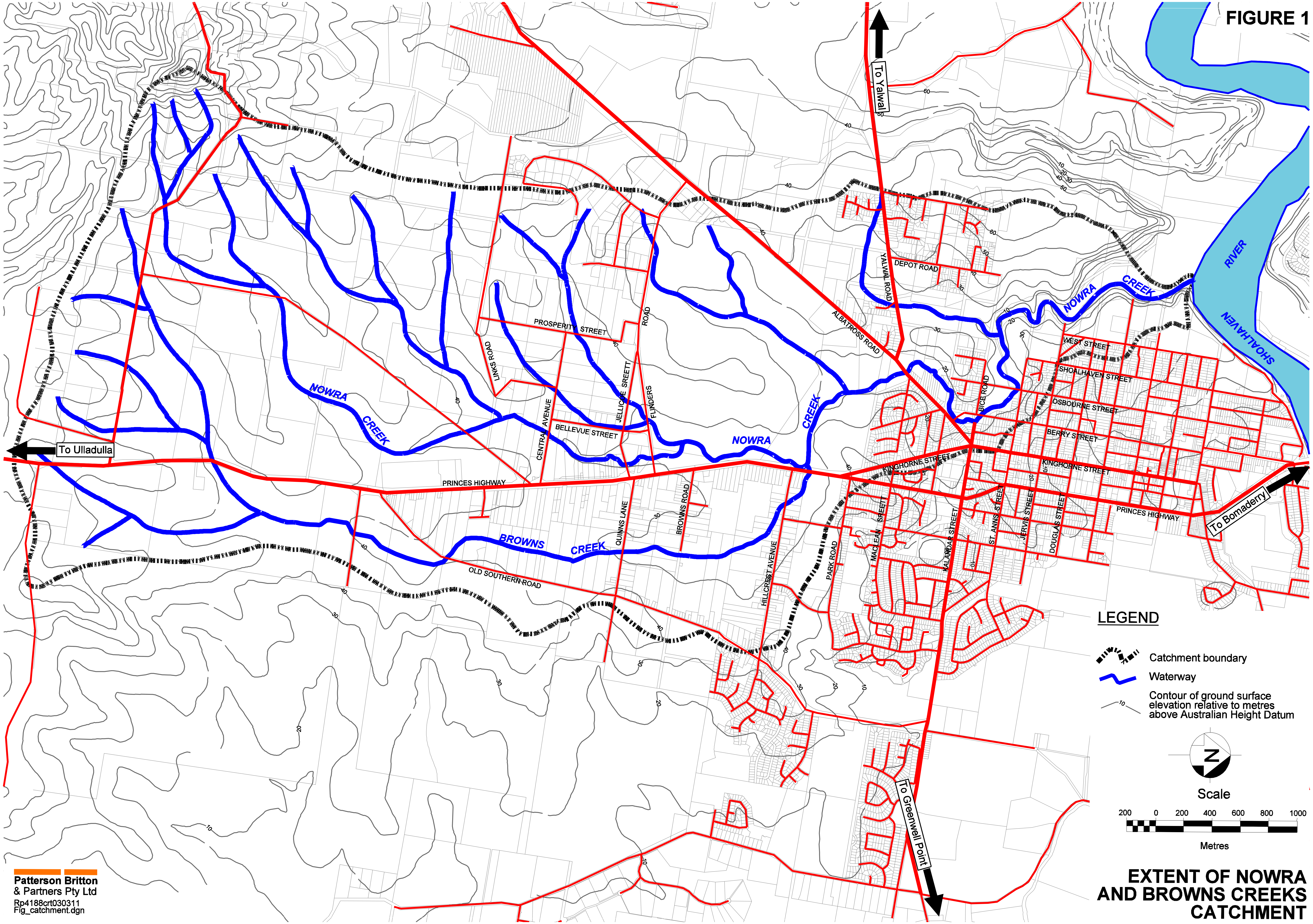

FIGURE 1

EXTENT OF NOWRA AND BROWNS CREEKS CATCHMENT

Patterson Britton & Partners Pty Ltd
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2 METHODOLOGY

Floodplain management in New South Wales generally follows guidelines established in the government's *'Floodplain Management Manual'* (*2001*). This document outlines the steps involved in the floodplain management process and the activities required to be undertaken to successfully develop a Floodplain Risk Management Plan for flood affected regions.

The *'Floodplain Management Manual'* states that the implementation of the State Government's *Flood Prone Lands Policy* requires a Floodplain Risk Management Plan that ensures:

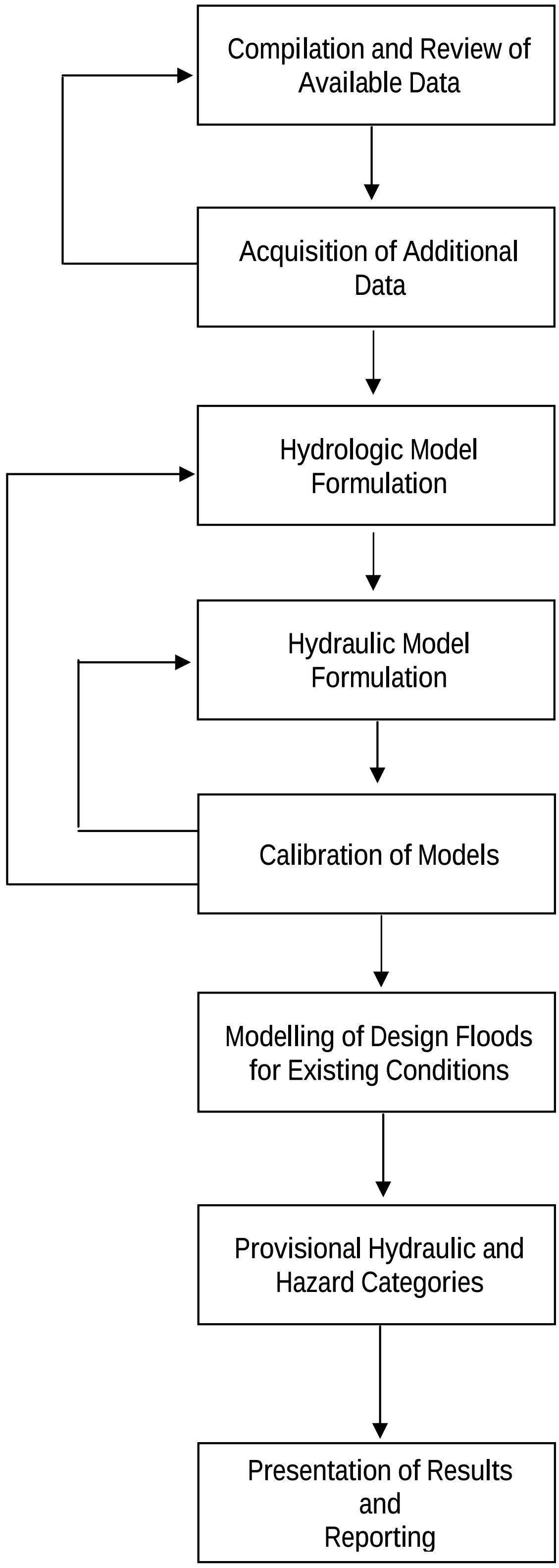
- the use of flood liable land is planned and managed in a manner compatible with the assessed frequency and severity of flooding;
- flood liable lands are managed having regard to social, economic and ecological costs and benefits, to individuals as well as to the community;
- floodplain management matters are dealt with having regard to community safety, health and welfare requirements;
- information on the nature of possible future flooding is conveyed to the public;
- all reasonable measures are taken to alleviate the hazard and damage potential resulting from development on floodplains;
- there is no significant increase in hazard and damage potential resulting from new development on floodplains; and,
- effective flood warning systems exist and emergency services are available to attend to flood affected communities in the event of future flooding.

One of the key steps involved in formulating a floodplain management plan is the recognition, definition and quantification of the principal factors associated with flooding. This information is presented in a Flood Study, which is a baseline document that summarises flood related data. This data can be used to resolve floodplain management issues and prevent poor planning and inappropriate development.

The aim of the Flood Study is to produce information on flood flows, velocities, levels and flood extents, for a range of flood events under existing floodplain and catchment conditions. A secondary aim is for the study to highlight those areas where the greatest flood damage is likely to occur.

The objective of this report is to characterise flood behaviour in the Nowra Creek catchment as it affects the urban and industrial areas of Nowra and South Nowra. It includes an analysis of the hydrologic characteristics of the catchments of both Nowra and Browns Creeks and a detailed analysis of the hydraulics of floodwater movement along the creeks and their floodplains.

The flow chart shown overleaf outlines the key steps and the sequence of work that has been undertaken in preparing this Flood Study.


Compilation and Review of Available Data
Acquisition of Additional Data
Hydrologic Model Formulation
Hydraulic Model Formulation
Calibration of Models
Modelling of Design Floods for Existing Conditions
Provisional Hydraulic and Hazard Categories
Presentation of Results and Reporting

3 REVIEW OF AVAILABLE DATA

3.1 PREVIOUS INVESTIGATIONS

A number of previous investigations have been undertaken to examine the nature and extent of flooding along Nowra and Browns Creeks. These include flood studies and investigations that are documented in the following reports:

- *'Lower Shoalhaven River Flood Study'* (*1990*)
- *'Flood Studies for South Nowra Industrial Estate and Nowra Creek'* (*1991*)
- *'Shoalhaven River Design Flood Profiles - Burrier to Nowra'* (*1992*)
- *'Review of Hydraulic Investigations on Nowra Creek Downstream of Jellicoe Street'* (*1999*)
- *'Nowra Creek at Whites Bridge on Albatross Road'* (*2000*)
- *'Bridge Waterway Options at Central Avenue on Nowra Creek'* (*2001*)

These investigations typically provide estimates of peak 100 year ARI flood levels at a range of locations along each of the two major streams in the catchment.

However, an underlying tenet of the *'Floodplain Management Manual'* (*2001*) is the need to consider all floods up to and including the probable maximum flood (*PMF*). None of the investigations listed above assessed the full range of floods that can occur or considered the extent of potentially flood liable land along the full length of the creek system.

Notwithstanding, all of the listed investigations provide useful information and flood related data. A brief synopsis of the reports prepared for each is presented in the following sections.

3.1.1 Review of Previous Flood Studies

Lower Shoalhaven River Flood Study (*1990*)

Synopsis

In 1990, a flood study of the Lower Shoalhaven River was undertaken by the then NSW Department of Public Works to determine design flood levels for the 20, 50 and 100 year average recurrence interval (ARI) design floods. The study area extended from a point 2 kilometres upstream of the Princes Highway bridge crossing of the Shoalhaven River at Nowra to the Tasman Sea at both Shoalhaven Heads and Crookhaven Heads.

The flood study was based on computer modelling of hydrologic processes and flood hydraulics. The WBNM software was used to simulate hydrologic processes and the CELLS modelling software was used to simulate flood hydraulics and estimate peak flood levels. A considerable amount of historical data was available including rainfall and stream flow records, historical flood levels and ocean/tidal records. This data was used to calibrate both the hydrologic and hydraulic models, which in turn were used to determine design flows, and peak flood levels and velocities.

Relevance

The *'Lower Shoalhaven Flood Study'* (*1990*) is directly applicable to this investigation despite its not considering flood hydraulics along Nowra or Browns Creeks.

The report provides peak flood level data at the confluence of Nowra Creek and the Shoalhaven River which is useful for setting downstream tailwater conditions in any modelling of flooding along Nowra Creek. For example, by interpolating between adopted design flood levels for Riverside Park and the Princes Highway bridge, it is possible to estimate peak design flood levels at the confluence of Nowra Creek and the Shoalhaven River.

The results presented in the 1990 report were interpolated to determine peak flood levels at the confluence for each of the 20, 50 and 100 year ARI design flood events and an extreme design flood event. These are listed in **Table 1**. These levels are in good agreement with those documented in the report titled, *'Shoalhaven River Design Flood Profiles - Burrier to Nowra'* (*May, 1995*).

Table 1 ADOPTED DESIGN FLOOD LEVELS AT NOWRA CREEK / SHOALHAVEN RIVER CONFLUENCE

DESIGN FLOOD EVENT	ADOPTED PEAK DESIGN FLOOD LEVEL AT CONFLUENCE (*mAHD*)
20 Year ARI	5.8
50 Year ARI	6.6
100 Year ARI	7.5
Extreme Event	11.2

Flood Studies for South Nowra Industrial Estate and Nowra Creek (*1991*)

Synopsis

Lyall & Macoun Consulting Engineers (*LMCE*) was engaged by Shoalhaven City Council to prepare a flood study for an area of land within the South Nowra Industrial Estate. The parcel of land was bound by Central Avenue in the south, Jellicoe Street in the north and Prosperity and Bellevue Streets in the west and east respectively.

The aim of the investigation was to develop options for controlling flood flows and to determine measures for managing future encroachment into the floodplain for development. LMCE also defined the extent of the 100 year ARI design flood for the upper reaches of Nowra Creek and the potential reduction in flood level due to channel clearing.

The study used the RORB hydrologic software package and a 2D dynamic hydraulic model called FPLAIN, to calculate 100 year ARI design flood levels along the upper reaches of Nowra Creek.

The report also detailed a concept design for floodways within South Nowra.

Relevance

The 1991 Report contains some relevant information detailing historical flood marks in the area. These flood marks were identified during the December 1989 flood and were surveyed as part of the investigation. The flood occurred in response to heavy rainfall over the catchment on 5th December 1989.

LMCE were unable to calibrate their models to reproduce the recorded flood levels using realistic model parameters and historic rainfall records. No attempt was therefore made to either calibrate or verify the models used in this present study to these recorded 1989 flood levels.

Other items of relevance include:

- The Probabilistic Rational Method was used to determine peak discharges along Nowra Creek. The peak 100 year ARI design flood discharge at Flinders Road was determined to be 140 m^3/s. This is based on a time of concentration of 1.5 hours. The current study has not assessed whether or not this estimate is considered reliable.
- Sections of the channel of Nowra Creek within the investigation area were found to be heavily overgrown and hydraulically inefficient. The report indicated that channel clearing would be beneficial in terms of providing improved conveyance capacity.
- The LMCE report identified a major storm on 5th December 1989, which resulted in significant flooding throughout the catchment. LMCE were unable to calibrate their models to reproduce the recorded flood levels using realistic model parameters and historic rainfall records. This storm was therefore reported as being approximately equivalent to the 100 year ARI event simply because the recorded levels approximated the computed profile.

Shoalhaven River Design Flood Profiles - Burrier to Nowra (*1995*)

Synopsis

In 1995, the then NSW Public Works prepared a brief report detailing design floodwater surface profiles for the Burrier to Nowra section of the Shoalhaven River. The report formed an extension to the *'Lower Shoalhaven River Flood Study'* (*1990*) which defined peak design flood levels for the area downstream between the Princes Highway bridge crossing at Nowra and Shoalhaven Heads.

The profiles were generated to assist Council in its implementation of the NSW Government's *Flood Prone Land Policy* and specifically for the assessment of development proposals along the river.

Floodwater surface profiles were generated for the 50 and 100 year ARI floods and an extreme event. The hydrologic analysis was based on application of the WBNM rainfall runoff model that had originally been developed for the *'Lower Shoalhaven River Flood Study'* (*1990*). Peak flood levels were generated by routing catchment discharge hydrographs determined from the WBNM model, through a MIKE-11 model of the river and floodplain between Burrier and Nowra.

The WBNM model was calibrated to streamflow records for the Grassy Gully gauge. Flood records for the following floods were used in the calibration:

- August 1974;
- June 1975;
- October 1976;
- March 1978; and,
- April/May 1988.

The calibration process led to the adoption of initial and continuing losses of 30 mm and 2 mm/hr, respectively. Recorded flood levels for the 1974, 1975 and 1978 floods were used to calibrate and verify the MIKE-11 hydraulic model. Difficulty was experienced in matching recorded and simulated flood levels at a number of gauges. However, an acceptable correlation was established and the model was used to simulate the range of design floods and the generation of design flood profiles for the area between Burrier and Nowra.

The report concluded that the simulated data reproduced historical flood levels to within 0.5 metres at most locations and that this was acceptable given the limited amount and quality of calibration data available.

Relevance

The 1995 Report relates specifically to the Shoalhaven River upstream from the Princes Highway bridge crossing. Although Nowra Creek drains to this reach of the Shoalhaven River, the report does not detail peak flood levels along Nowra Creek. Notwithstanding, it does provide peak flood level data at the confluence of Nowra Creek and the Shoalhaven River which is useful for setting downstream tailwater conditions in any modelling of flooding along Nowra Creek. The adopted tailwater levels for the Nowra Creek confluence are presented in **Table 1**.

The 1995 Report also documents recorded flood levels for the 1974, 1975 and 1978 floods. These are listed in **Table 2** and provide useful data for computer model calibration.

Table 2 HISTORICAL FLOOD LEVELS

LOCATION ALONG THE SHOALHAVEN RIVER	RECORDED PEAK FLOOD LEVEL (*mAHD*)		
	1974	1975	1978
Riverside Park	6.6	-	7.4
Princes Highway Bridge at Nowra	4.9	4.9	5.3

Review of Hydraulic Investigations on Nowra Creek Downstream of Jellicoe Street (*1999*)

This report was not available at the time of writing and therefore could not be critiqued.

Nowra Creek at Whites Bridge on Albatross Road (*2000*)

Synopsis

Hyder Consulting was commissioned by Shoalhaven City Council to undertake a Flood Study of Nowra Creek between the Albatross Road crossing (*known as Whites Bridge*) and the Berry Street crossing. The objective of the investigation was to determine peak flood levels and to compare these with existing road levels and thereby establish the frequency of overtopping.

A hydrologic model of the catchment upstream from Albatross Road was developed using the RORB software package. As no historical stream flow data was available for model calibration, peak flood discharges were estimated using the Probabilistic Rational Method and parameters in the RORB model were adjusted to produce the same peak discharge at the catchment outlet.

The HEC-RAS software was used to develop a one dimensional hydraulic model of the channel between the two bridges. The model was based on existing cross-sectional data held by Council and was used to simulate flood levels for a combination of flow conditions with varying road elevations, culvert dimensions and waterway areas.

Relevance

This study produced design flood levels for the 10, 20, 50 and 100 year ARI floods along a 1.4 kilometre stretch of Nowra Creek extending downstream from Whites Bridge.

The investigation determined that Albatross Road is typically flooded at Whites Bridge and at the junction with Berry Street in events rarer than the 5 year ARI flood. This was reported as being due to a combination of inadequate waterway area and low bridge / roadway approach embankments.

The analysis also determined that Nowra Creek rises to its peak discharge over a period of approximately 2 hours. The design peak discharges determined from the hydrologic modelling are listed in **Table 3** and the peak flood levels generated from the HEC-RAS modelling are listed in **Table 4**.

Table 3 PREDICTED PEAK DISCHARGES AT WHITES BRIDGE (*after HYDER*)

LOCATION	PEAK FLOOD DISCHARGE (*m^3/s*)				
	5 Year ARI	10 Year ARI	20 Year ARI	50 Year ARI	100 Year ARI
Whites Bridge	130	182	223	267	294
Catchment Outlet	133	184	226	277	310

Table 4 PREDICTED PEAK FLOOD LEVELS AT WHITES BRIDGE (*after HYDER*)

LOCATION	PEAK FLOOD LEVEL (*mAHD*)				
	5 Year ARI	10 Year ARI	20 Year ARI	50 Year ARI	100 Year ARI
Whites Bridge	20.3	21.3	21.7	21.8	21.9
Catchment Outlet	17.6	17.9	18.2	18.5	18.6

Bridge Waterway Options at Central Avenue on Nowra Creek (*June 2001*)

Synopsis

Lyall & Associates were commissioned by Shoalhaven City Council to undertake an investigation into flooding in the vicinity of the Central Avenue bridge crossing of Nowra Creek in South Nowra.

The RORB rainfall-runoff model developed for a previous investigation undertaken by Lyall & Macoun Consulting Engineers in March 2000 was employed to estimate peak flows for events ranging in frequency from 5 to 100 year ARI.

A HEC-RAS steady state backwater model was also developed to generate water surface profiles for the range of flood frequencies considered. The hydraulic model was used to estimate profiles under both present day conditions and for a proposed modification to the bridge crossing that incorporated a 500 mm rise in the crest level of Central Avenue.

Relevance

Predicted peak discharges determined from the hydrologic modelling for the range of design floods are listed in **Table 5**.

Table 5 PREDICTED PEAK DISCHARGES AT CENTRAL AVENUE (after LYALL)

LOCATION	PEAK FLOOD DISCHARGE (m^3/s)			
	5 Year ARI	10 Year ARI	20 Year ARI	50 Year ARI
Central Avenue crossing	40	62	75	104

The investigation determined that the existing road would be inundated in floods rarer than the 5 year ARI event. This was considered to be due to elevated tailwater conditions resulting from a lack of hydraulic capacity in the Nowra Creek channel immediately downstream of Central Avenue.

As the bridge crossing has now been upgraded, the information presented in the 2001 Report is of limited value to this current investigation. However, the cross sectional data is of use and while design flood levels generated for the post bridge construction scenario could be used for comparison purposes, the current study has not done so.

3.2 REVIEW OF AVAILABLE DATA

Searches of Council records were undertaken during the course of the study to uncover as much flood related data as possible. A limited amount of background information was collected from Council held reports and some topographic mapping was uncovered from Council plan cabinets.

Requests for relevant flood related data were also lodged with the Department of Infrastructure, Planning & Natural Resources (*DIPNR*) (*formally the NSW Department of Land & Water Conservation*), along with other government agencies such the State Rail Authority (*SRA*) and the Roads and Traffic Authority (*RTA*).

All of the data supplied was compiled and assessed to determine its usefulness to this study. A discussion of the range of data that was uncovered is provided in the following sections.

3.2.1 Topographic Data

The topography of the Nowra and Browns Creeks catchment is defined on existing mapping. The available sources of data defining the topography of the catchment are:

- 1:25000 series topographic mapping developed by the Central Mapping Authority (*CMA*);
- Contour mapping of the area based on aerial photogrammetry undertaken in the mid 1980s and presented on 1:2000 series orthophoto mapping sheets of the area; and,
- oblique and vertical aerial photography.

Aerial Photography

Council possesses a number of sets of aerial photography for the entire catchment, spanning the last thirty years. These photographs provide details of land use and can be used to define geomorphic characteristics of the floodplain across the study area.

The most recent aerial photography was flown in 1997 and stereoscopic pairs of contact prints are available for this run.

Contour Mapping

The 1:2000 series orthophoto mapping of the area is available from Council's GIS and provides contours at 2 metre intervals, as well as spot elevations at selected locations.

3.2.2 Hydrographic Data

Only limited existing hydrographic survey data was available for use in this study.

A number of areas of Nowra Creek and its floodplain have been surveyed as part of previous flood investigations. The most recent of these was undertaken in March 2000 as part of investigations into flooding of Nowra Creek at Whites Bridge, which is located along Albatross Road (*refer* **Figure 1**). This survey provided hydrographic and topographic data across the area between Osborne Street and Albatross Road. Plots of cross-sections that were gathered along the creek are included within **Appendix A**.

In 1991, a survey was also carried out between the Central Avenue and Flinders Road crossings of Nowra Creek (*refer* **Figure 1**). The cross-sections gathered as part of this survey are also included within **Appendix A**. Unfortunately, it was not possible to uncover the raw cross-sectional data (*i.e., offsets and levels*) gathered as part of this survey.

Consultations with a local surveyor indicated that cross-sections of Browns Creek were surveyed in 1990. These cross-sections were surveyed along the length of the creek between the four wheel drive track located north of Snowwood Road, to BTU Road. Unfortunately the raw cross-sectional data was not available to this study.

Design details of all relevant culverts and bridges along the creeks are available from Council records. These were obtained and copies of drawings showing the details of bridge crossings are included within **Appendix B**.

3.2.3 Historical Flood Marks

A number of the previous flood investigations that have been completed for the Nowra Creek catchment placed considerable emphasis on collecting available historical data as well as anecdotal evidence of specific flood events.

In recognition of the importance of anecdotal information, a questionnaire was prepared as part of this study and distributed to the community. A copy of the questionnaire that was developed for the study is enclosed within **Appendix C**. It contains four primary questions and was specifically targeted toward obtaining additional historical flood information.

A summary of the responses to the questionnaire is included within **Appendix D**. Reliable flood level data gathered from these responses is listed in **Table 6** and the locations of associated flood marks are shown in **Figure 3**.

Table 6 RECORDED LEVELS ALONG NOWRA CREEK FOR THE 1978 FLOOD

LOCATION (*refer* Figure 3)	RECORDED 1978 FLOOD LEVEL (*m AHD*)
1. Upstream side of Central Avenue culvert	33.94
2. Bellevue Street near entrance to drive-in theatre	32.43
3. Upstream side of Flinders Road Bridge	29.26
4. Southern end of Berry Street	18.88
5. Backyard of Forrester residence (Berry Street)	18.09
6. Northern most Berry Street crossing of Nowra Creek	18.09

NB. The stated levels were based on photographic and anecdotal reports from residents of Nowra and were surveyed by DPWS.

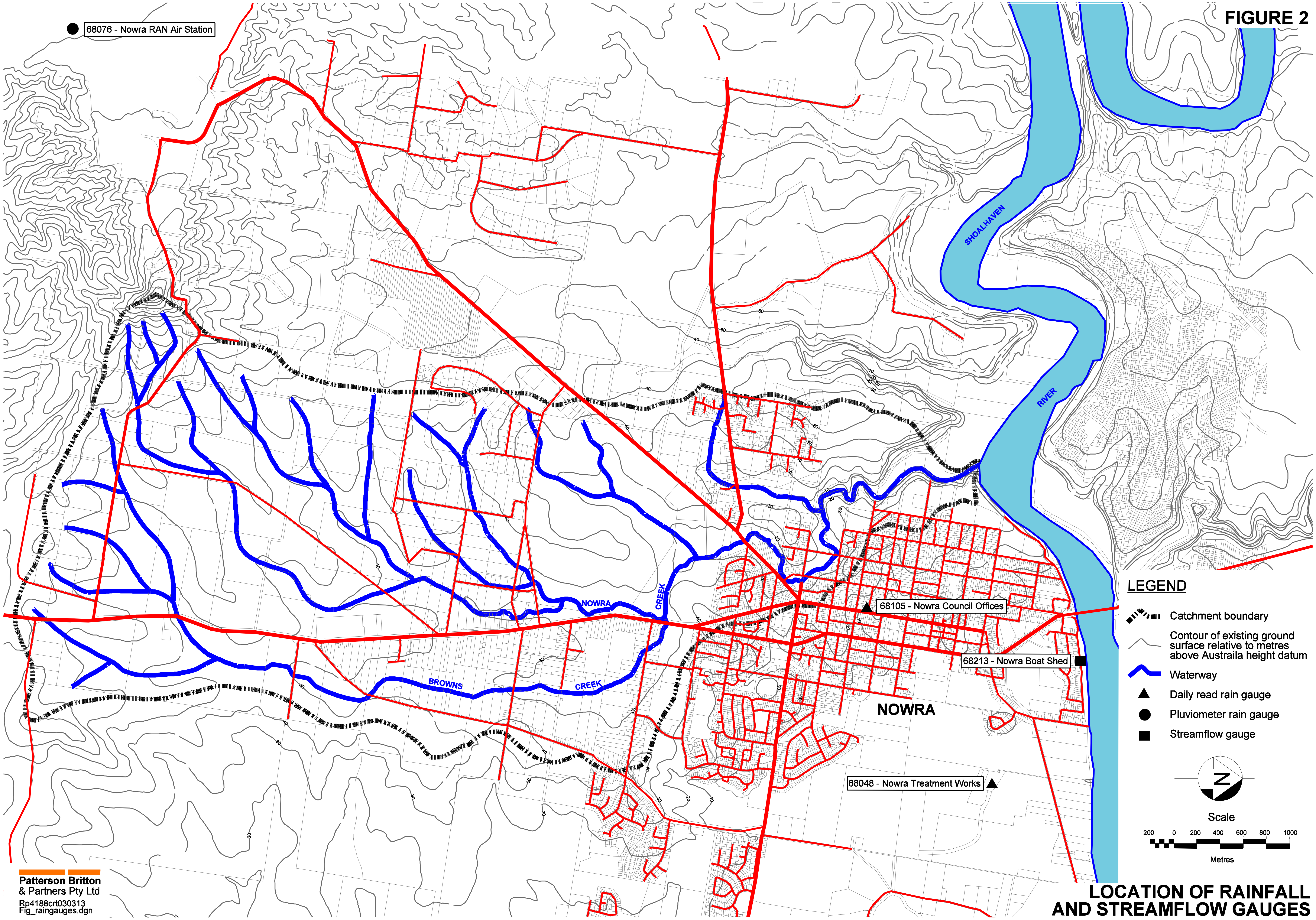
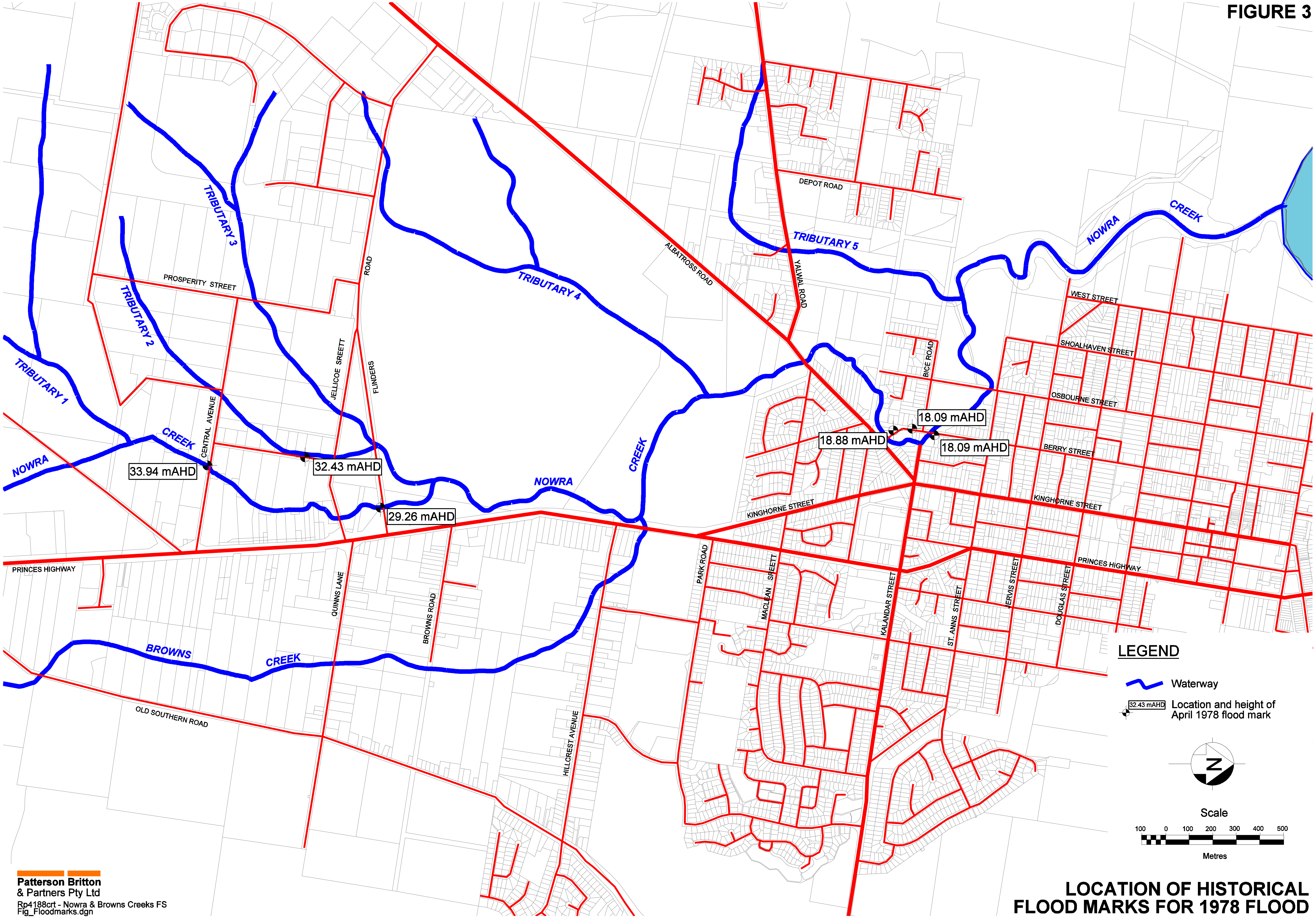


FIGURE 2

LOCATION OF RAINFALL AND STREAMFLOW GAUGES



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LOCATION OF HISTORICAL FLOOD MARKS FOR 1978 FLOOD

3.2.4 Hydrologic Data

As discussed, major flooding in the Nowra and Browns Creeks catchment has occurred in 1974, 1978, 1989 and 1999. Data collected for these floods, such as peak flood levels and rainfall patterns, can be used to check the validity of results generated by computer models developed to simulate flood behaviour.

Therefore, as part of the review of available data, efforts were made to identify all relevant rainfall and streamflow data that could be compiled for use in the study.

Due to significant uncertainty as to the reliability of historical flood level information reported in earlier studies discussed previously, the current investigation has been restricted to use of flood level information for the 1978 flood derived from responses to the questionnaire that was distributed.

Historical Rainfall Records

Continuous rainfall data for specific storms is required for the calibration and verification of hydrologic computer models. This data is usually obtained from pluviometers located within the catchment being modelled. Pluviometers generate pluviographs which are plots of the instantaneous variation in rainfall with time.

The nearest pluviometer to the study area is located at the Nowra RAN Air Station (***refer* Figure 2**). Although this pluviometer is not located within the Nowra and Browns Creeks catchment, it is considered that it is situated sufficiently close to the study area to provide a reliable representation of catchment rainfall.

There is also potential to account for localised variations in rainfall across the catchment by utilising rainfall data from other rainfall gauges. Apart from pluviometers, rainfall is measured in rain gauges that are read on a daily basis by individuals entrusted to monitor rainfall.

Although there are no daily read rainfall gauges situated within the catchment, there are several gauges located adjacent to the catchment, with records extending over 100 years. The location of these daily read rainfall gauges are shown in **Figure 2**.

Streamflow Records

Streamflow data is generated from rating curves for gauging stations that are usually located along streams and rivers. A time series record of flood level over the duration of a flood is generated at these gauging stations and the corresponding rating table is used to generate a discharge hydrograph. The discharge hydrograph provides a measure of the rate of flow at any particular time during a flood.

Unfortunately there are no streamflow gauges located along either Nowra or Browns Creeks so no streamflow records were available for use in the present study.

4 HYDROLOGIC ANALYSIS

4.1 HYDROLOGIC MODEL DEVELOPMENT

The Runoff Analysis and Flow Training Simulation (*RAFTS-XP*) software package was employed to quantify flood discharges from the Nowra and Browns Creeks catchment.

RAFTS-XP is a deterministic runoff routing model that simulates catchment runoff processes. It is recognised in *'Australian Rainfall and Runoff – A Guideline to Flood Estimation'* (*1987*), as one of the available tools for use in flood routing within Australian catchments.

RAFTS-XP was chosen for this investigation because it has the following attributes:

- it can account for spatial and temporal variations in storm rainfalls across a catchment;
- it can accommodate variations in catchment characteristics;
- it can be used to estimate discharge hydrographs at any location within a catchment; and,
- it has been widely used across eastern NSW and therefore, where suitable calibration data is not available, the results from modelling of other similar catchments can be used as a guide in the determination of model parameters.

The RAFTS-XP model was developed using the physical characteristics of the catchment including catchment area, slope, roughness, percentage impervious area and vegetation density and type. It was used to estimate sub-catchment runoff peaks and to generate discharge hydrographs for tributary inflows to Nowra and Browns Creeks.

These tributary inflows form the upstream boundary conditions for the proposed hydraulic model.

4.1.1 Sub Catchment Details

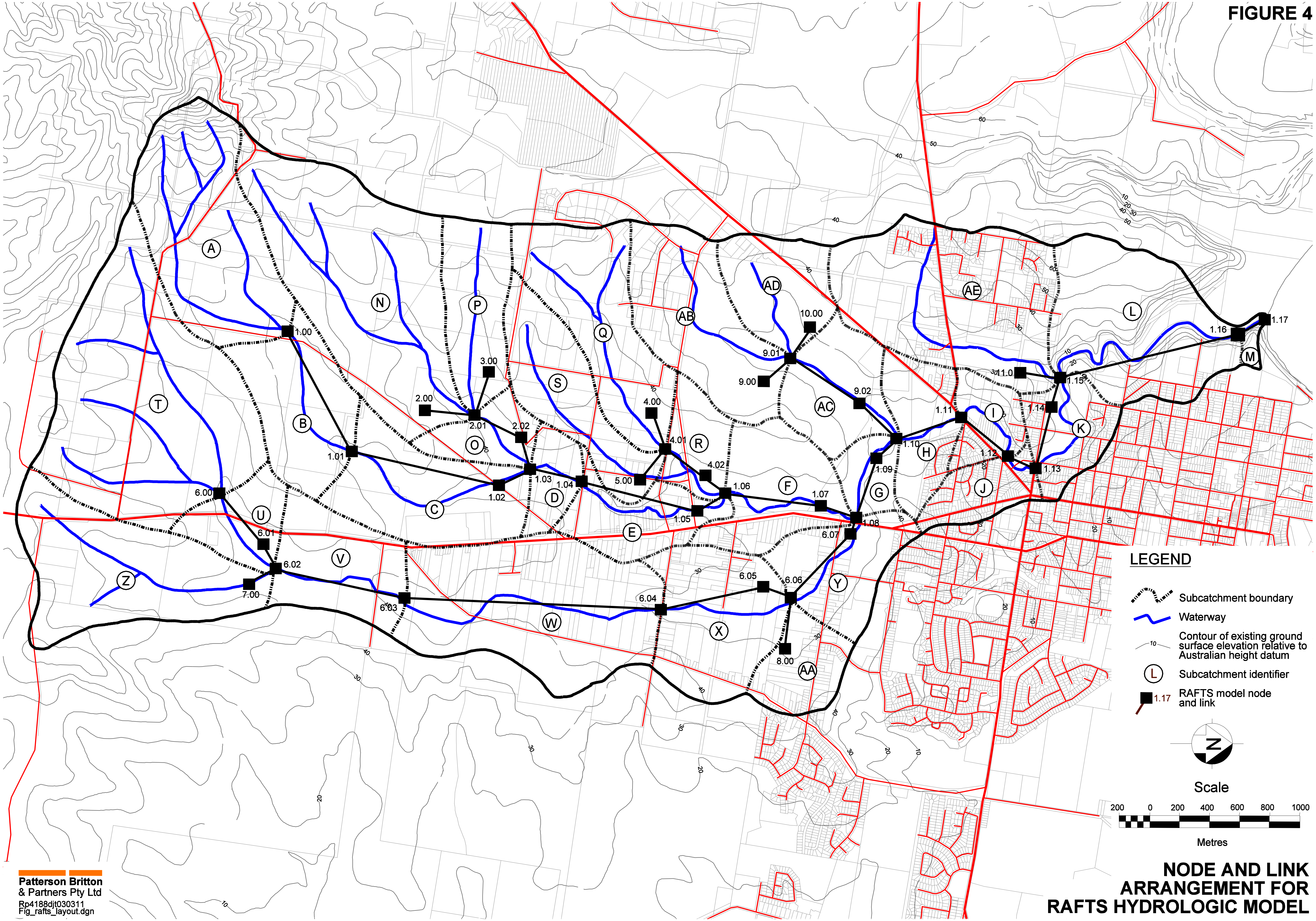
The Nowra and Browns Creeks catchments were divided into sub-catchments differentiated on the basis of the alignment of major tributary flow paths and watershed boundaries, as well as the homogeneity of land-use, vegetation and ground slope.

Catchment break-up was also designed so that the downstream points of sub-catchments draining to the lower potion of the catchment coincided with the likely location of inflow points for the proposed hydraulic model.

Parameters such as sub-catchment area, slope and percentage impervious area were established from the available data and assigned to each sub-catchment. A listing of the range of sub-catchment parameters incorporated within the model is provided in **Appendix E**.

The adopted catchment break-up and model layout is shown in **Figure 4**.

FIGURE 4



NODE AND LINK ARRANGEMENT FOR RAFTS HYDROLOGIC MODEL

4.1.2 Rainfall Loss Model

In a typical storm event, not all of the rainfall that falls onto the catchment is converted to runoff. Depending on the prevailing "wetness conditions" of the catchment at the commencement of the storm (*i.e., antecedent wetness conditions*), some of the rainfall may be lost to the groundwater system through infiltration into the soil, or may be intercepted by vegetation and stored. This component of the overall rainfall is considered to be "lost" from the system and does not contribute to the estimated catchment runoff.

To account for rainfall losses of this nature, a rainfall loss model can be included within the RAFTS-XP model. For this study, the *Initial-Continuing Loss Model* was used to simulate rainfall losses across the catchment.

This model assumes that a specified amount of rainfall (*e.g., 10 mm*) is lost from the system in the initial stages of the storm being considered, and that further regular losses occur at a specified rate per hour (*e.g., 5 mm/hr*). These further losses are referred to as continuing losses which aim to account for infiltration and interception by vegetation once the catchment is saturated. These rainfall losses are effectively deducted from the total rainfall over the catchment, thereby leaving the remaining rainfall to be distributed through the watershed as runoff.

As no definitive loss rate data is available for the Nowra and Browns Creeks catchment, rainfall loss rates used in the modelling were based on recommendations outlined in the RAFTS User Manual and documented in *'Australian Rainfall and Runoff'* (*1987*). Sensitivity analyses were also undertaken to ensure that the adopted values provided reliable estimates of peak flood discharges. Adopted loss rates for each sub-catchment within the RAFTS model are listed in **Table E1** of **Appendix E**.

It should be noted that initial and continuing losses of 4 mm and 2 mm/hr, respectively, were adopted for pervious areas of the catchment. In contrast, the hydrologic modelling undertaken for the *'Lower Shoalhaven River Flood Study'* (*1990*) was based on the adoption of initial and continuing losses of 30 mm and 2 mm/hr, respectively.

Hence, it is considered that the hydrologic analysis of the Nowra Creek catchment is based on suitably conservative estimates of infiltration.

4.2 HYDROLOGIC MODEL CALIBRATION

Flood routing models such as RAFTS should be calibrated and verified using rainfall and streamflow data from specific flood events. Rainfall records from a major storm that caused flooding are input into the model to reflect the variability of rainfall over the catchment through the course of the storm.

Model calibration is undertaken by routing rainfall excess for a particular storm through the model and generating discharge hydrographs at locations where streamflow records for the flood corresponding to the storm, have been gathered. Calibration is completed by adjusting model parameters to achieve the best match between recorded and model generated discharge hydrographs.

4.2.1 Calibration Data

Rainfall Data

Continuous rainfall data for specific storms is required for the calibration and verification of hydrologic computer models. As discussed in **Section 3.2.4**, there are no pluviometers located within the Nowra and Browns Creeks catchment. However, there is a pluviometer located at HMAS Albatross which is about 10 kilometres south of the catchment. There are also several daily read rain gauges located in closer proximity to the catchment.

A comparison between the total rainfall measured by the pluviometer and the daily read gauges was conducted to check for spatial variation in rainfall across the Nowra and Browns Creek catchment and adjacent areas. The comparison showed little difference between total rainfall suggesting that the pluviograph data could be applied to the Nowra and Browns Creeks catchments.

The comparison also suggested that a spatially uniform rainfall pattern could be applied. This assumption is considered to be reasonable due to the relatively small size of the Nowra and Browns Creek catchment.

Streamflow Data

As discussed in **Section 3.2.4**, no streamflow gauges exist within the Nowra and Browns Creeks catchment. Therefore, even though rainfall data is available for multiple storm events, the lack of any streamflow records makes reliable calibration of the hydrologic model difficult.

Notwithstanding, it is possible to employ techniques to achieve a "pseudo-calibration" by comparison of hydraulic model results with recorded flood levels for historical floods. This process involves adjusting both parameters within both the hydrologic and hydraulic models until the flood levels predicted by the hydraulic model agree with recorded historic flood levels.

4.2.2 Simulation of the 1978 Flood

Once the RAFTS hydrologic model was established, calibration was attempted using daily read rainfall data recorded during the April 1978 storm. During this storm, a total of 220 mm of rainfall fell over a 24 hour period, causing significant flooding within the Nowra and Browns Creeks catchment.

A temporal pattern, representing the time varying distribution of rainfall over the duration of the storm event, was applied to the total depth of rainfall that fell during the 1978 storm.

Initial loss rates were applied from anecdotal reports of catchment wetness. Continuing loss rates were then adjusted during the calibration process so that discharge hydrographs used in the hydrologic modelling and routed through the hydraulic model replicated recorded flood levels for the 1978 event. Catchments with a high vegetation density were assumed to intercept more runoff and would therefore have larger loss rates.

It was also assumed that the majority of the catchment was pervious, particularly within the upstream or southern areas.

A second "impervious sub-area" was added to each sub-catchment within the urbanised areas to account for the differing runoff characteristics that were likely to have existed in these areas at the time of the flood. Different initial and continuing loss rates were applied to the pervious and impervious sub-areas of each sub-catchment.

RAFTS model simulation of the 1978 storm generated a peak discharge at the downstream end of the model (*i.e., near the confluence of Nowra Creek and the Shoalhaven River*) of about 200 m^3/s. There have been no previous attempts to determine the peak discharge during the 1978 flood and no stream gauging was undertaken. Hence, it is not possible to comment on the reliability of this estimate of peak flow at the catchment outlet.

4.3 HYDROLOGIC MODEL VERIFICATION

Due to significant uncertainty as to the reliability of historical flood level information reported in earlier studies discussed previously, the current investigation had no reliable data with which to attempt verification of the models developed.

4.4 SENSITIVITY ANALYSIS

In the absence of reliable historical rainfall data for model calibration, an assessment was made of the sensitivity of predicted discharges to antecedent catchment wetness conditions and variations in continuing loss rates. Details of the sensitivity analysis are provided in the following sections.

4.4.1 Catchment Wetness

The degree of catchment wetness prior to a storm is important as it determines the extent to which rainfall can infiltrate the soil surface. The groundwater systems of catchments, which are saturated prior to a major storm, will have less capacity to absorb rainfall. Therefore, under wet antecedent (*i.e., prior to a storm*) conditions, there will be less "loss" of rainfall to the groundwater systems, and consequently more runoff. Hence, high or saturated antecedent wetness conditions will generally cause the highest flood discharges.

An assessment of the sensitivity of predicted model discharges to catchment wetness can be made based on variations to sub-catchment rainfall loss rates. Based on field observations of catchment condition, the limited literature on hydrologic model loss rates, and the calibration performed in the previous section, it was decided that the representative loss rates for the RAFTS model sub-catchments should be those listed in **Table 7**.

Table 7 ADOPTED LOSS RATES FOR RAFTS HYDROLOGIC MODEL

CATCHMENT	LOSS RATES	
	Initial Loss (mm)	Continuing Loss (mm/hour)
Pervious areas	4	2
Impervious areas	1	0

In order to confirm the suitability of these loss rates, an assessment of the sensitivity of the model to variability in initial loss rates across the catchment was made. The assessment was based on a comparison of modelled discharges along the major tributaries within the catchment for the 1978 flood event for a wet and dry catchment scenario.

The adopted losses for each model run and a comparison of resultant peak discharges at selected locations are listed in **Table 8**.

Table 8 MODEL SENSITIVITY TO VARIATION IN CATCHMENT WETNESS

RAFTS MODEL SUB-CATCHMENT IDENTIFIER	RAFTS MODEL NODE AT DOWNSTREAM END OF CATCHMENT	PEAK DISCHARGE (*m³/s*)		
		Adopted Design Losses (*IL=4 / 1, CL=2 / 0*)	Wet Catchment Conditions (*IL=2 / 0, CL=2 / 0*)	Dry Catchment Conditions (*IL=8 / 2, CL=2 / 0*)
M	1.17	200.7	200.7	200.7

The results listed in **Table 8** indicate that a reduction in the adopted loss rates to reflect saturated catchment conditions results in no change in peak discharge from the catchment for the 1978 flood. Similarly, increasing the loss rates to model a storm occurring on a dry catchment, had no effect on peak discharge at the catchment outlet.

Hence, it can be concluded that the initial rainfall loss rates adopted in the model have no significant impact on flood discharge estimates for the Nowra and Browns Creeks catchment.

4.4.2 Variation in Continuing Loss Rate

Sensitivity runs were also carried out to assess the impact of variations to the continuing loss rates on peak discharges. Continuing rainfall losses were varied to reflect the two most extreme vegetation density conditions; viz:

- the occurrence of the 1978 storm over the catchment with a uniformly sparse vegetation distribution; and,
- the occurrence of the 1978 storm over the catchment with a uniformly dense vegetation distribution.

The dense vegetation distribution will have the ability to intercept more runoff and will therefore produce a higher continuing loss rate than the sparse vegetation distribution.

The results of these model simulations are presented in **Table 8**.

The results show that by increasing the continuing loss rates to reflect dense vegetation across the catchment, the peak 1978 storm discharge at the catchment outlet is decreased by approximately 5%. The results also show that by decreasing the rainfall loss to represent a sparse vegetation distribution, the peak 1978 storm discharge could be increased by around 3%.

Table 9 MODEL SENSITIVITY TO VARIATION IN CONTINUING LOSS RATES

RAFTS MODEL SUB-CATCHMENT IDENTIFIER	RAFTS MODEL NODE AT DOWNSTREAM END OF CATCHMENT	PEAK DISCHARGE (*m^3/s*)		
		Adopted Design Losses (*IL=4 / 1, CL=2 / 0*)	Sparse Vegetation (*IL=4 / 1, CL=1 / 0*)	Dense Vegetation (*IL=4 / 1, CL=4 / 0*)
M	1.17	200.7	205.5	191.6

Based on this analysis it can be concluded that the continuing rainfall loss rates adopted in the hydrologic model can have a minor impact on flood discharge estimates for the Nowra and Browns Creeks catchment.

4.4.3 Conclusion

Based on the sensitivity analyses completed for this investigation, it appears that peak discharge estimates generated by the RAFTS hydrologic model are slightly sensitive to variations in continuing rainfall loss rates.

However, the two scenarios presented in the sensitivity analysis can be considered to represent extreme conditions, and therefore may be regarded as providing the upper and lower bound estimates of possible peak discharges for the 1978 storm.

Due to the relative insensitivity of the hydrologic model to variation in loss rates, it was concluded that the original loss rates documented in **Table 7** should be adopted.

5 HYDRODYNAMIC MODEL DEVELOPMENT

5.1 GENERAL

The RMA-2 (*Resource Management Associates, USA*) suite of software was employed to simulate flood behaviour along the Nowra and Browns Creeks system. RMA-2 is a fully two dimensional finite element model developed by Resource Management Associates of the USA and Prof. Ian King of the University of California at Davis.

RMA-2 was chosen for this investigation over other modelling techniques because it has the following attributes:

- RMA-2 is a fully two dimensional finite element model, hence it allows for overland flow to be modelled within the floodplain;
- it uses finite element methods to solve 2D depth averaged equations for turbulent energy losses, friction losses and horizontal momentum transfer, and as such offers significant benefits over the more traditional finite difference techniques;
- it uses a variable grid geometry employing elements with irregular and curved boundaries which can be modified as required without the need for regeneration of the entire grid, this enables any shaped boundary to be modelled exactly;
- it permits the simulation of systems that flood and dry during the analysis period.

The RMA-2 model developed for this study was used to simulate the passage of floodwaters through the township and thereby predict flood characteristics such as peak flood level and flow velocity. It was also applied to determine provisional hydraulic and hazard categories.

5.2 MODEL DEVELOPMENT

To enable development of a RMA-2 model capable of simulating flood behaviour within the study area, additional topographic and hydrographic definition of the Nowra and Browns Creeks channels and floodplain was required. The Survey Section of the Department of Commerce (*formerly the Department of Public Works & Services*) was engaged to gather the additional survey data.

The additional data comprised the survey of cross-sections of the channel and floodplain, and details of hydraulic structures likely to influence flood behaviour (*such as bridge and culvert crossings*). It also involved the survey of roadways and historic flood marks.

A total of 55 cross-sections were gathered as part of the study. This included 46 cross-sections of both Nowra and Browns Creeks and their floodplains. Long sections of Princes Highway, Central Avenue, Warra Warra Road, Jellicoe Street, Flinders Road, Quinns Lane, Browns Road, Hillcrest Avenue, Albatross Road and Berry Street, were also obtained. Details of the additional cross-sectional data are contained in **Appendix F**.

Details of ten (10) bridge and culvert crossings of both Nowra and Browns Creeks were also gathered as part of the survey. This included the details of crossings at Central Avenue, Flinders Road, the Princes Highway, Albatross Road and Berry Street. Cross-sections of the channel were also obtained at points downstream of each bridge and culvert crossing in order to ensure that the waterway area was sufficiently defined and bridge affluxes were reliably modelled.

Thirteen (13) flood marks recorded during the April 1978 and 1999 floods were also surveyed based on photographic and anecdotal information. The locations of the surveyed historic flood marks are shown in **Figure 3**.

5.2.1 Network Development

The RMA-2 model network that was developed for the study extends from The Links Road crossing of Nowra Creek and the Warra Warra Road crossing of Browns Creek, downstream to the confluence of Nowra Creek and the Shoalhaven River. The higher topography on the western and eastern side of the creek floodplains defined the lateral extent of the model network.

An approximation consisting of two rectangular finite elements was used to define the upper Nowra and Brown Creeks channels. The lower reaches of Nowra Creek (***i.e.,*** *downstream of Albatross Road*) were approximated using four finite elements. Conveyance calculations were performed to ensure that the conveyance of the channels was not compromised by using this approximation method.

The size and location of floodplain finite elements were determined based on the definition required within the model and the topography of the floodplain. The finite element grid was aligned with the cross-sections taken along the creeks to enable flood heights and velocities to be related back to the location of these cross-sections. The extent of the hydraulic model network and location of creek cross-sections are shown in **Figure 5**.

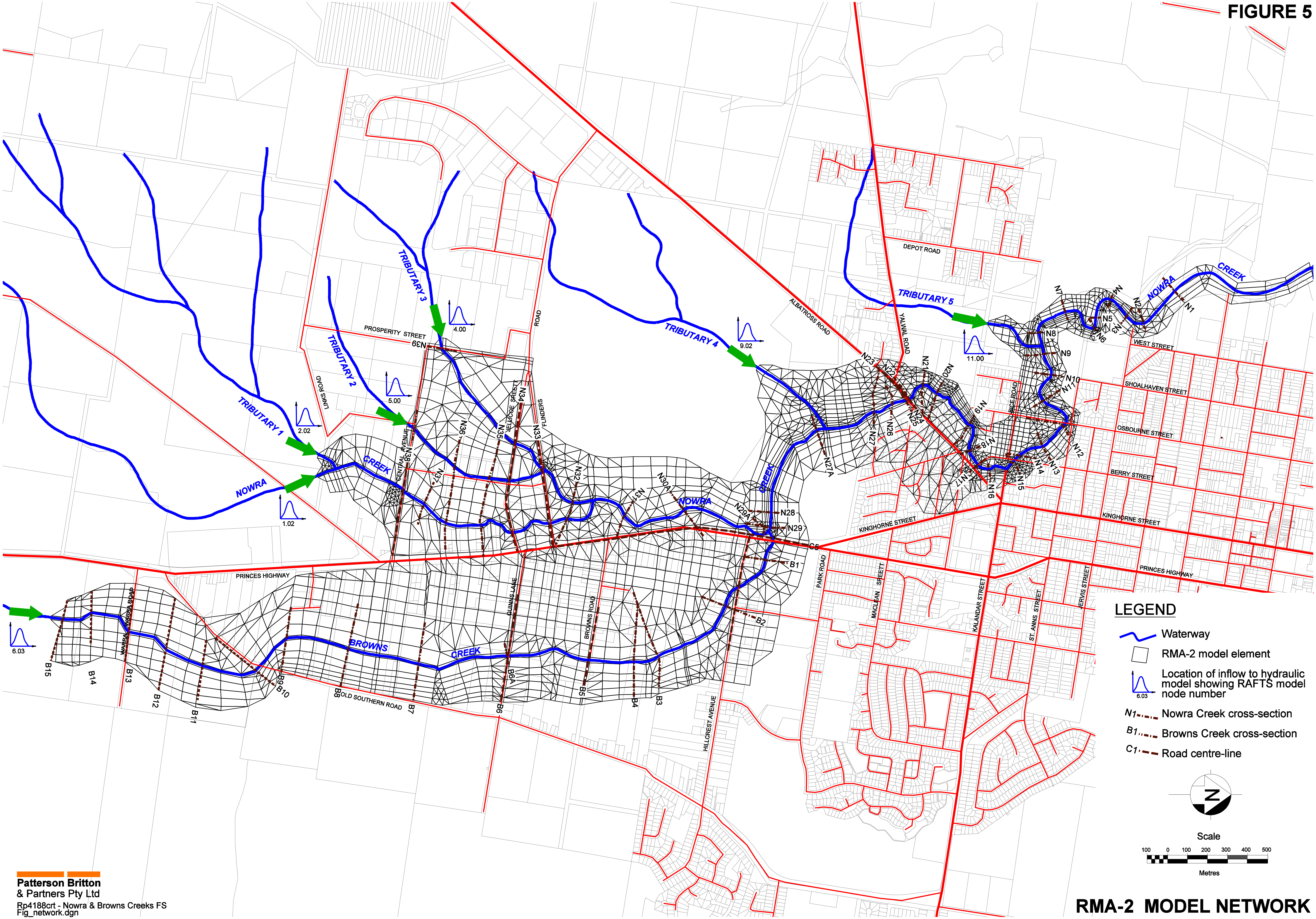
5.2.2 Channel and Floodplain Roughness Parameters

Main channel and overbank roughness parameters were determined for the study area from aerial photograph analysis and from field observations of channel and floodplain vegetation density.

The roughness values were initially assessed by comparing vegetation density and land use observed in the field, with standard photographic records of stream and floodplain condition for which Manning's "n" roughness values are documented in the literature. This was supplemented by a sensitivity analysis which considered increases in roughness parameter value and application of these values to determine the potential impact on peak flood levels.

Discussion of the analyses of hydraulic model sensitivity to roughness parameters are presented in Sections 5.3.2 Additional Calibration Investigations and 6.2.3 Sensitivity Analysis. Comparative flood profiles are presented in **Appendix J**.

FIGURE 5



RMA-2 MODEL NETWORK

Nowra Creek

The channel and floodplain of Nowra Creek upstream of The Links Road (*refer* **Figure 1**) are generally characterised by dense vegetation. The riparian corridor between The Links Road and Flinders Road is also relatively densely vegetated. However, this area forms part of the South Nowra Industrial Precinct and much of the floodplain has been cleared and comprises a mix of open pasture, paved surfaces and buildings.

The reach between Flinders and Albatross Roads (*refer* **Figure 1**) passes through Shoalhaven State Forest and densely vegetated Crown Land. The channel in this area is relatively incised and clothed in dense vegetation.

The area between Albatross Road and Jervis Street comprises mostly residential dwellings that adjoin the riparian corridor. The creek channel and immediate overbank areas are relatively densely vegetated, although there are intermittent sections of less dense overbank vegetation particularly between the Berry Street crossings of the main channel.

Browns Creek

Browns Creek is characterised by a less well defined channel within a relatively flat and open floodplain. Upstream of Old Southern Road (*refer* **Figure 1**), the floodplain has not been cleared for development.

The area between Old Southern Road and Hillcrest Avenue forms part of the South Nowra Industrial Precinct. This area has been cleared and comprises a mix of open pasture and buildings amidst sporadic pockets of larger trees. The channel is poorly defined and the "floodway" is effectively formed by a relatively wide and flat overbank area. This is largely cleared but there are areas where encroachment has occurred as part of development.

Between Hillcrest and the Princes Highway crossing of Browns Creek, the channel and floodplain are characterised by open pasture and moderately dense riparian corridor vegetation.

Initial Roughness Parameter Estimation

An initial assessment of roughness parameters was made based on the description outlined above and interpretation of available aerial photography. This assessment led to the adoption of a set of parameter values for different element types. The initial roughness parameter values are listed in **Table 10**.

Due to the complexity and variability of the catchment land use, roughness parameter values were based on a weighted average applied across relatively large areas. This was undertaken to simplify the initial modelling simulations while still providing a reasonable representation of hydraulic resistance.

Table 10 INITIAL HYDRODYNAMIC MODEL ROUGNESS PARAMETERS

RMA-2 ELEMENT TYPE	DESCRIPTION	ROUGHNESS PARAMETER
1	Creek channel with Heavy Bank Vegetation	0.045
2	Densely vegetated floodplain areas (*e.g., u/s of Albatross Road*)	0.080
3	Creek Channel with Low / Medium Density Bank Vegetation	0.035
4	Typical semi-urban floodplain areas	0.055

5.2.3 Model Boundary Conditions

Upstream and downstream boundary conditions are important for the successful simulation of flooding using a hydrodynamic model. Initial conditions are the depth and flow conditions the model starts a simulation with, while the boundary conditions simulate the physical boundaries of the model area as well as model inflows and outflows throughout the duration of the flood simulation.

Upstream Boundary Conditions

Upstream Boundary conditions are the flow conditions coming into the model such as hydrographs generated by the hydrologic model while downstream boundary conditions are the water level conditions at the downstream or outflow point of the model such as normal or critical depth conditions. As discussed in **Sections 3** and **4**, the upstream boundary conditions for the hydraulic model are provided by the discharge hydrographs generated from the RAFTS rainfall runoff model.

As shown in **Figure 5**, the hydraulic model extends across a large proportion of the Nowra and Browns Creeks catchment. Therefore, both major and minor tributary inflow must be accounted for by the hydraulic model to accurately simulate flood behaviour through the creek network.

Accordingly, in addition to major flows into Nowra and Browns Creek, five minor tributary inflows were also included within the hydraulic model. The locations of these inflows are identified within **Figure 5**. A description of each and the corresponding RAFTS model node number are listed in **Table 11**.

Downstream Boundary Conditions

Downstream boundary conditions within the RMA-2 hydraulic model are expressed in the form of time varying water levels at the downstream extent of the model. An accurate downstream water level is critical for developing reliable result through the remainder of the model.

The downstream boundary of the Nowra and Browns Creek hydraulic model coincides with the confluence of Nowra Creek and the Shoalhaven River. Accordingly, it is possible to assign a tailwater level for the Nowra and Browns Creeks model based on historic and design water surface profiles developed for the Shoalhaven River.

Peak flood levels generated as part of the *'Lower Shoalhaven River Flood Study'* (*1990*) are listed in **Table 1**. These were adopted to define tailwater conditions in the Nowra and Browns Creeks catchment for design flood simulations.

Table 11 UPSTREAM BOUNDARY CONDITIONS FOR HYDRAULIC MODEL

TRIBUTARY	LOCATION	RAFTS MODEL NODE REFERENCE
Brown Creek	Near Princes Highway / Warra Warra Road Intersection	6.03
Nowra Creek	Near confluence of Nowra Creek and Tributary 1	1.02
Tributary 1	Near confluence of Nowra Creek and Tributary 1	2.02
Tributary 2	Tributary 2 crossing of Central Avenue	5.00
Tributary 3	Tributary 3 crossing of Prosperity Street	4.00
Tributary 4	Northern end of Archer Racecourse	5.00
Tributary 5	Near western end of Bice Road	11.0

5.3 HYDRAULIC MODEL CALIBRATION

As discussed in **Section 3**, there are no stream gauges along either Nowra or Browns Creek. Hence, it was not possible to reliably calibrate the RAFTS hydrologic model that has been developed to predict peak floods flows and define flood discharge hydrographs. However, a "*pseudo-calibration*" can be performed by adjusting parameters within both the hydraulic and hydrologic models until simulated flood levels agree with historic flood levels.

A total of six historic flood marks were identified along Nowra Creek for the April 1978 flood. These flood marks were established as an outcome from responses to the questionnaire that was distributed to all residents and landowners within the catchment. These flood marks were surveyed by the Department of Commerce to define recorded flood levels at each location for the 1978 flood. Unfortunately, no historic flood marks were available along Browns Creek for this event. The location of flood marks collected for this study are presented in **Figure 3** and are also summarised within **Table 6**.

5.3.1 Initial Calibration Assessment

As outlined in **Section 4.2.2**, the RAFTS model was used with available rainfall records to simulate the storm that led to the flood that occurred in April 1978. The discharge hydrographs generated by the RAFTS model were input into the RMA-2 as upstream boundary conditions. The downstream water level was determined from water surface profiles for the Shoalhaven River which included peak water levels recorded during the 1978 flood.

The RMA-2 model was used to simulate the 1978 flood and an initial water surface profile was generated. This was based on the initial roughness parameters adopted for elements within the model network, which are listed in **Table 10**.

The initial assessment provided a reasonable "fit" between simulated and observed flood levels for the 1978 event. The water surface profile generated for the 1978 event from this initial analysis is shown in **Figure J1** of **Appendix J**.

A comparison between this profile and recorded flood levels is provided and shows a reasonable correlation, albeit that there are only a small number of historical flood marks and these are concentrated in "built-up" areas of the catchment. A direct comparison between simulated flood levels and recorded flood levels is also provided in **Table 12**.

Table 12 COMPARISON BETWEEN RECORDED AND SIMULATED FLOOD LEVELS USING INITIAL ROUGHNESS PARAMETER VALUES

WATERCOURSE	LOCATION*	1978 FLOOD LEVEL (*mAHD*)	SIMULATED FLOOD LEVEL (*mAHD*)	DIFFERENCE (*m*)
Nowra Creek	Upstream of Central Ave	33.94	33.97	0.03
Tributary 2	Upstream of Jellicoe Street	32.43	32.51	0.08
Nowra Creek	Upstream of Flinders Road	29.26	29.22	-0.04
Nowra Creek	160 m upstream of Bice Rd	18.88	18.69	-0.19
Nowra Creek	50 m upstream of Bice Rd	18.09	18.27	0.18
Nowra Creek	Downstream of Bice Road	18.09	18.00	-0.09

**** The location of historic flood marks are identified in*** Figure 3

Table 12 shows that simulated flood levels upstream of the bridge, which therefore include afflux, are within 80 mm of recorded flood levels for the 1978 flood.

This suggests that the peak discharge generated by the RAFTS model and the roughness parameters adopted within the RMA-2 model are acceptable but low as demonstrated by the water surface profile in **Figure J1**, which is contained in **Appendix J**.

In the vicinity of Bice Road and Berry Street, the agreement is not as good. As shown in **Table 12**, a maximum discrepancy of 190 mm exists between recorded and simulated flood levels. Notwithstanding, historic and simulated flood levels generally agree with one another to within 100 mm.

5.3.2 Additional Calibration Investigations

Since the simulated flood water surface profiles were generally below the recorded flood levels, an additional calibration investigation was undertaken to assess whether it was possible to achieve a better "fit" to recorded flood marks for the 1978 flood. This involved a re-assessment of the roughness parameters initially adopted for the hydraulic model and listed in **Table 10**.

The re-assessment led to further refinement of the model network and the introduction of additional element types to represent a greater array of vegetation and land use types. The analysis was undertaken on a trial basis in conjunction with a sensitivity analysis aimed at determining the influence of channel and overbank roughness on predictions of peak flood level. It also involved further inspection of available aerial photographs of the study area and site inspections to verify contemporary creek and floodplain vegetation density and land use.

The additional calibration investigation process led to the adoption of eight different model element types to represent the floodplain and riparian corridor of Nowra and Browns Creeks. These element types are listed and described with the roughness parameter values assigned to each in **Table 13**.

Table 13 ADOPTED HYDRODYNAMIC MODEL ROUGHNESS PARAMETERS

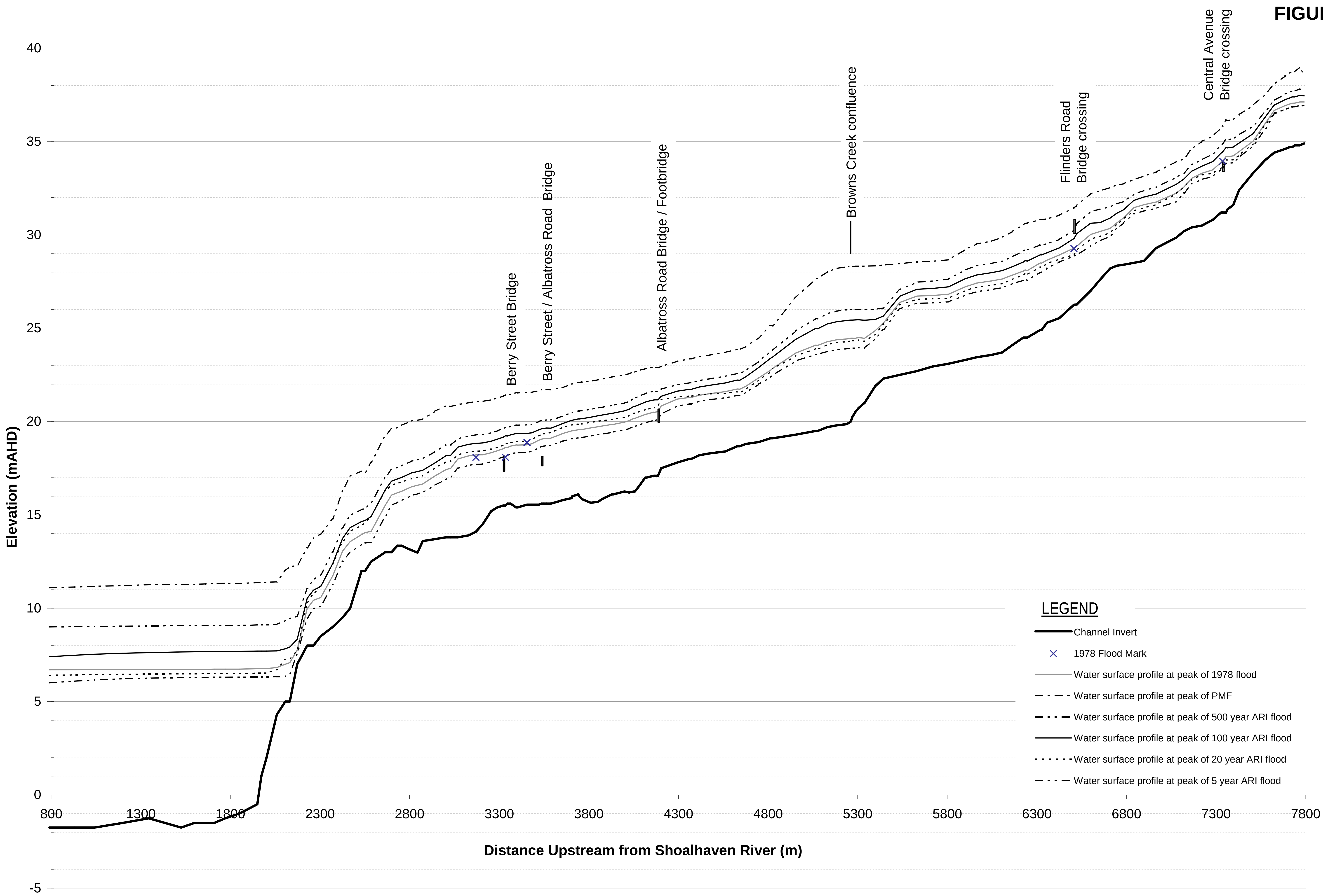
RMA-2 ELEMENT TYPE	DESCRIPTION	ROUGHNESS PARAMETER
1	Creek channel with heavy brush on banks	0.050
2	Floodplain with light tree coverage	0.045
3	Floodplain with dense tree coverage	0.110
4	Urban Sections of the Floodplain	0.030
6	Floodplain with medium tree coverage	0.080
7	Roadways	0.015
8	Grassed floodplain	0.033

The roughness parameter values identified in Table 13 were adopted within the RMA-2 model network and the refined model was used to re-simulate the 1978 flood. Peak flood level estimates were extracted from the results of the modelling and were used to generate the water surface profiles shown in **Figures 6** and **7** for Nowra and Browns Creeks, respectively.

A comparison between the water surface profiles generated using the initial roughness parameters and the revised roughness parameters is also provided in **Figures J1** and **J2**, which are contained in **Appendix J**. It is notable from **Figure J1** that the water surface profile generated using the initial roughness parameters listed in **Table 10** falls below the recorded flood marks at all locations except the Berry Street bridge crossing. The water surface profile generated using the revised roughness parameters listed in **Table 13** generally show close agreement with the recorded flood marks.

A direct comparison between simulated flood levels upstream of the bridges (*using the revised roughness parameter values*) and recorded flood levels at the bridges, is also presented in **Table 14**.

FIGURE 6



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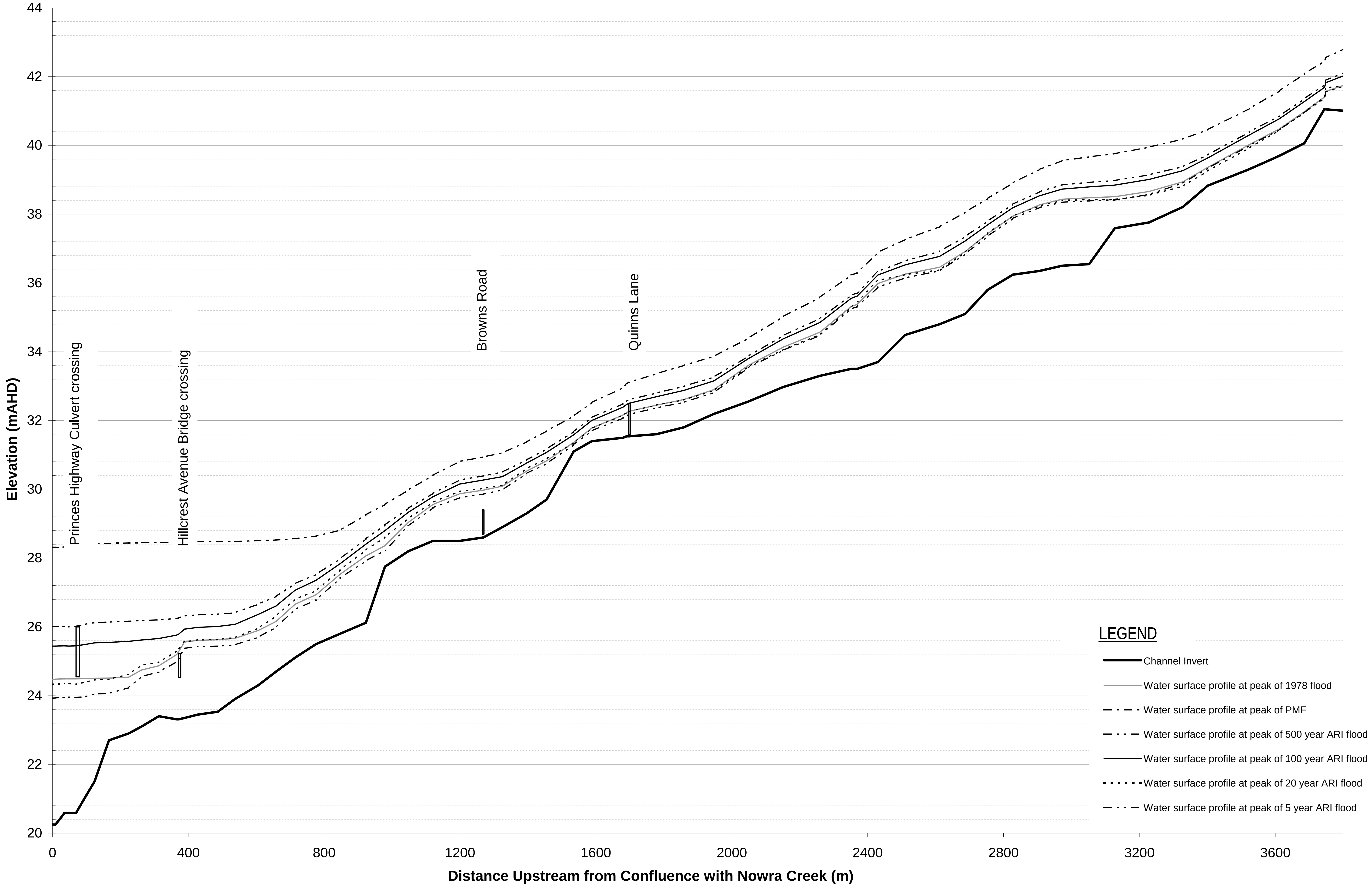
rp4188 - Nowra & Browns Creeks Flood Study
WS Profile - Nowra Creek
Water Surface Profile-Nowra & Browns Crk - 5, 20, 100 & 500 yr - FINAL DRAFT.xls

WATER SURFACE PROFILES FOR NOWRA CREEK

FIGURE 7



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rp4188 - Nowra & Browns Creeks Flood Study
WS Profile - Browns Creek
Water Surface Profile-Nowra & Browns Crk - 5, 20, 100 & 500 yr - FINAL DRAFT.xls

WATER SURFACE PROFILES FOR BROWNS CREEK

Table 14 would indicate that the revised roughness parameter values generated a good correlation between simulated flood levels and historic flood levels if the reported flood levels were at the bridge rather than in the upstream afflux region. Generally simulated flood levels and historic flood levels agreed to within 120 mm.

However, there was one significant departure between simulated and recorded flood levels. This occurred in the vicinity of the Berry Street bridge crossing of Nowra Creek. The difference between simulated and historic flood levels at this location is about 0.5 metres.

However, it should be noted that this particular flood mark was based on anecdotal evidence which stated that "the floodwaters covered the crown of the road" (*refer* **Appendix D**). The anecdotal advice did not specify the depth of floodwaters over the road.

Therefore, the surveyed flood mark was assumed to correspond to the elevation of the crown of the road. However, the actual flood level could haven been higher, which would have resulted in better agreement between simulated and actual historic flood leve ls at this location.

Table 14 COMPARISON BETWEEN RECORDED AND SIMULATED FLOOD LEVELS USING ADOPTED ROUGHNESS PARAMETER VALUES

WATERCOURSE	LOCATION*	1978 FLOOD LEVEL (*mAHD*)	SIMULATED FLOOD LEVEL (*mAHD*)	DIFFERENCE (*m*)
Nowra Creek	Upstream of Central Ave	33.94	34.04	0.10
Tributary 2	Upstream of Jellicoe St	32.43	32.31	-0.12
Nowra Creek	Upstream of Flinders Rd	29.26	29.29	0.03
Nowra Creek	160 m upstream of Bice Rd	18.88	18.82	-0.06
Nowra Creek	50 m upstream of Bice Rd	18.09	18.59	0.50
Nowra Creek	Downstream of Bice Road	18.09	18.20	0.11

** The location of historic flood marks are identified in* **Figure 3**

The results of the calibration simulations indicate that the revised roughness values provide a more realistic estimate of peak flood levels along Nowra Creek than the initial estimates.

However, since the reported flood levels generated upstream of the bridges in the area subject to afflux are generally slightly higher than the peak levels recorded at the bridges in the 1978 flood (*refer* **Table 14** *and* **Figure 6**), some may argue that the revised roughness parameters would appear to provide a more conservative assessment of peak flood levels along Nowra and Browns Creeks.

Notwithstanding that there are anecdotal reports indica ting that the density of vegetation along the riparian corridor has increased since 1978, the revised roughness parameter values listed in **Table 13** were considered to account for contemporary conditions and were adopted for the simulation of design floods.

However, before the design flood simulations were undertaken, a further simulation was undertaken for the 1978 flood as part of the sensitivity analysis to assess the impact of further increases to the adopted roughness values. This analysis involved increasing the roughness value assigned to element type 3 (*i.e., floodplain with dense tree coverage*) to provide a theatrical 'upper bound' for the most densely vegetated sections of the catchment under contemporary conditions. The element parameter values that were adopted for this simulation are listed in **Table 15**.

The results of the simulation are superimposed on the water surface profiles in **Figures J1** and **J2** of **Appendix J**. The water surface profiles shown in **Figure J1** indicate that the increased roughness values generated slightly higher estimates of peak flood level along most of the length of Nowra Creek. **Figure J2** indicates that the change in profile along Browns Creek is so slight as to be undetectable at the plotted scale. This accords with LMCE's 1991 finding that their FPLAIN model was relatively insensitive to variations in floodplain roughness in the 0.12 to 0.15 range. The increases are generally predicted to be less than 150 mm.

It was also noted that this analysis produced a poorer correlation between simulated and historic flood levels which is reassuring as the **Table 15** roughness parameters were intended to simulate contemporary rather than 1978 conditions.

Accordingly, this analysis reinforced the adoption of the roughness parameters listed in **Table 13** for calibration purposes. It also suggests that those roughness parameters listed in **Table 15** would be appropriate for contemporary conditions if the reported increase in riparian vegetation density since 1978 has occurred.

Table 15 'UPPER BOUND' HYDRAULIC MODEL ROUGHNESS PARAMETERS

RMA-2 ELEMENT TYPE	DESCRIPTION	ROUGHNESS PARAMETER
1	Creek channel with heavy brush on banks	0.050
2	Floodplain with light tree coverage	0.045
3	Floodplain with dense tree coverage	0.150
4	Urban Sections of the Floodplain	0.030
6	Floodplain with medium tree coverage	0.080
7	Roadways	0.015
8	Grassed floodplain	0.033

A further sensitivity analysis was also undertaken as part of the design flood simulations to assess the impact that the adopted roughness values would have on more severe floods (*i.e., floods rarer than the 1978 flood*). This analysis is presented in the following section.

5.4 HYDRAULIC MODEL VERIFICATION

Due to significant uncertainty as to the reliability of historical flood level information reported in earlier studies discussed previously, the current investigation had no reliable data with which to attempt verification of the models developed.

6 DESIGN FLOOD ESTIMATION

6.1 HYDROLOGY

6.1.1 Design Simulations

The RAFTS model described in **Section 4** was used to simulate runoff from the catchment for design storm conditions. The design storm conditions were based on rainfall intensities and temporal patterns for the study area, which were derived using standard procedures outlined in *'Australian Rainfall and Runoff – A Guide to Flood Estimation' (1987)* (*ARR87*).

The design storm rainfall data was generated by applying the principles of rainfall intensity estimation described in Chapter 2 of ARR87. Intensity-frequency-duration data for Nowra were developed using these procedures and are enclosed in **Appendix F**.

Design temporal patterns outlined in ARR87 for the Nowra region were also adopted. These temporal patterns specify the distribution of the rainfall over the duration of the design storms.

A range of storm durations were considered and modelled to establish the critical storm duration for the catchment. The critical storm duration was assumed to correspond to the maximum peak discharge at the confluence of Nowra Creek and the Shoalhaven River as generated using the RAFTS model.

A critical storm duration of 2 hours was determined for the Nowra and Browns Creeks catchment for the design 5, 10, 20, 50, 100 and 500 year ARI storms. A critical storm duration of 3 hours was determined for the Probable Maximum Flood (*PMF*).

Peak discharges and hydrographs were generated throughout the catchment for a range of flood frequencies using the critical storm duration of 2 hours and the corresponding rainfall intensities and design temporal patterns. In accordance with the Study Brief, these flood frequencies included the 5, 10, 20, 50, 100 and 500 year ARI events, as well as the Probable Maximum Flood (*PMF*). A discussion of the methods used to derive the PMF is provided in **Section 6.2.3.**

6.1.2 Hydrologic Modelling Results

Peak Discharges

Peak catchment discharges determined using the RAFTS hydrologic model for Nowra Creek are listed in **Table 16**. Peak discharges along Browns Creek are listed in **Table 17**. The peak discharges listed in both tables are referenced to the RAFTS model node identifiers, which can be located by reference to **Figure 4**.

A complete listing of the output generated by the RAFTS model is provided in **Appendix H.**

Table 16 PEAK FLOWS FOR NOWRA CREEK SUB-CATCHMENTS BASED ON 2 HOUR CRITICAL STORM DURATION

SUB-CATCHMENT	RAFTS MODEL NODE NUMBER	PEAK DISCHARGE			
		5 Year ARI	20 Year ARI	100 Year ARI	PMF*
A	1.00	18.0	28.5	43.2	151.6
B	1.01	24.4	38.8	58.9	217.8
C	1.02	30.8	49.3	74.4	284.5
P	3.00	5.6	8.9	13.1	57.4
N	2.00	16.2	25.8	39.4	173.6
-	2.01	21.5	34.7	52.5	230.0
O	2.02	24.5	38.9	58.3	252.8
-	1.03	54.8	86.2	127.6	517.6
D	1.04	56.2	88.1	130.3	531.3
E	1.05	57.8	90.2	133.3	549.0
S	5.00	4.1	6.1	9.1	68.9
Q	4.00	8.5	12.7	19.4	89.6
-	4.01	12.6	18.8	28.2	158.5
R	4.02	15.8	24.3	35.8	186.4
-	1.06	68.2	105.1	155.2	655.0
F	1.07	70.9	108.5	159.7	682.1
-	1.08	141.4	216.0	320.1	1030.2
G	1.09	141.7	216.5	320.7	1035.1
AD	10.00	5.2	8.1	11.9	54.3
AB	9.00	11.9	17.7	25.4	101.9
-	9.01	16.3	24.5	35.6	156.2
AC	9.02	21.0	32.5	48.0	200.1
-	1.10	146.2	224.4	331.7	1096.7
H	1.11	146.6	225.1	332.7	1108.1
I	1.12	146.7	225.3	332.9	1113.0
J	1.13	146.8	225.4	333.0	1116.6
K	1.14	146.9	225.5	333.2	1119.3
AE	11.0	27.1	39.2	53.8	169.91
-	1.15	147.2	226.2	333.9	1127.4
L	1.16	147.5	226.5	334.3	1130.7
M	1.17	147.5	226.5	334.3	1130.7

**Critical storm duration for PMF event was 3 hours*

Table 17 PEAK FLOWS FOR BROWNS CREEK SUB-CATCHMENTS BASED ON 2 HOUR CRITICAL STORM DURATION

SUB-CATCHMENT	RAFTS MODEL NODE NUMBER	PEAK DISCHARGE			
		5 Year ARI	20 Year ARI	100 Year ARI	PMF*
T	6.00	44.3	63.1	85.7	267.4
U	6.01	47.7	68.8	93.9	295.3
Z	7.00	9.9	16.0	24.6	108.8
-	6.02	56.1	83.0	116.4	391.3
V	6.03	61.7	91.9	129.5	431.2
W	6.04	69.1	103.5	147.6	500.9
X	6.05	72.5	107.8	155.7	527.3
AA	8.00	4.2	103.5	9.2	40.0
-	6.06	73.6	109.3	158.6	538.0
Y	6.07	74.4	110.3	160.4	551.2

**Critical storm duration for PMF event was 3 hours*
NB For node and catchment locations refer to Figure 4.

The results show that the peak 100 year ARI storm discharge for Nowra Creek at the Shoalhaven River confluence, is 331 m^3/s. The 20 year ARI and 5 year ARI flood discharges are predicted to be about 227 m^3/s and 148 m^3/s, respectively. The peak PMF discharge from the catchment is estimated to be 1131 m^3/s.

Discussion

As discussed in **Section 4.2**, it is customary to calibrate hydrologic models to recorded streamflow data for major historic floods (*such as the 1978 flood*). However, in situations where there is insufficient streamflow data for calibration, it is prudent to compare the generated model discharges with results derived from other empirical discharge estimation methods. These empirical discharge estimation methods are based on recorded data for catchments of a particular size, type and location within Australia. They were developed prior to the regular application of rainfall runoff modelling techniques to determine flood discharges.

One commonly applied method is the ***Probabilistic Rational Method***, which is documented in detail in ***'Australian Rainfall & Runoff'*** (*1987*). This method comprises simple mathematical formulae that recognise catchment area, rainfall intensity and catchment roughness. However, it is only applicable to predominantly rural catchments and can only be used to predict a peak discharge. That is, it does not provide any definition of the rate of rise of floodwaters and is not directly applicable to an unsteady flow hydraulic model such as RMA-2.

The Probabilistic Rational Method (*PRM*) was applied to the Nowra and Browns Creeks catchment and used as a check on the peak discharges generated using the RAFTS model.

The comparison is provided in **Table 18**. It shows that the RAFTS model generally predicts lower discharges than the PRM.

Table 18 COMPARISON OF RAFTS AND THE RATIONAL METHOD PEAK DISCHARGES

LOCATION	RAFTS MODEL NODE NUMBER	RAFTS MODEL (m^3/s)		RATIONAL METHOD (m^3/s)	
		100 year ARI	20 year ARI	100 year ARI	20 year ARI
Confluence of Nowra Ck and the Shoalhaven River	1.17	334.3	226.5	367.7	275.7

Nonetheless, on the basis that the 20 year ARI results presented in **Table 18** agree within 20% and the 100 year ARI results within 10%, it can be concluded that the RAFTS model generates realistic estimates of peak discharges from the catchment for the 20 and 100 year ARI flood events.

6.2 HYDRAULIC MODELLING

6.2.1 Design Simulations

The RMA-2 two-dimensional hydrodynamic model of Nowra and Browns Creeks system was used to simulate flood behaviour for the design 5, 10, 20, 50, 100 and 500 year ARI events, and the probable maximum flood (*PMF*).

Upstream boundary conditions were defined by inflow hydrographs developed using the RAFTS hydrologic model (*refer above*). The adopted upstream boundary conditions are provided in **Appendix I**. For example, the design 100 year ARI event flood discharge hydrographs for tributary inflows were extracted from the RAFTS model output and used to define the rate of flow into the area covered by the hydraulic model.

These hydrographs were based on the results of hydrologic modelling for the critical storm duration which was determined to be 2 hours. An assessment of the impact of longer storm durations was also carried out to establish whether the resultant greater volume of flow would increase peak flood levels along the creek system.

This assessment found that the highest peak flood levels were generated with discharge hydrographs based on the 2 hour storm duration event. This is expected because the flood profile along Nowra and Browns Creeks is relatively steep and therefore momentum effects influence flow conveyance.

The downstream boundary condition was based on the design floodwater surface profiles generated previously for the Shoalhaven River.

6.2.2 Results

General

The hydraulic modelling provided design floodwater levels, depths, velocities and provisional hazard through the Nowra and Browns Creek system for each of the flood frequencies considered. The resulting flood profiles along Nowra and Browns Creeks are presented in **Figure 6** and **7**.

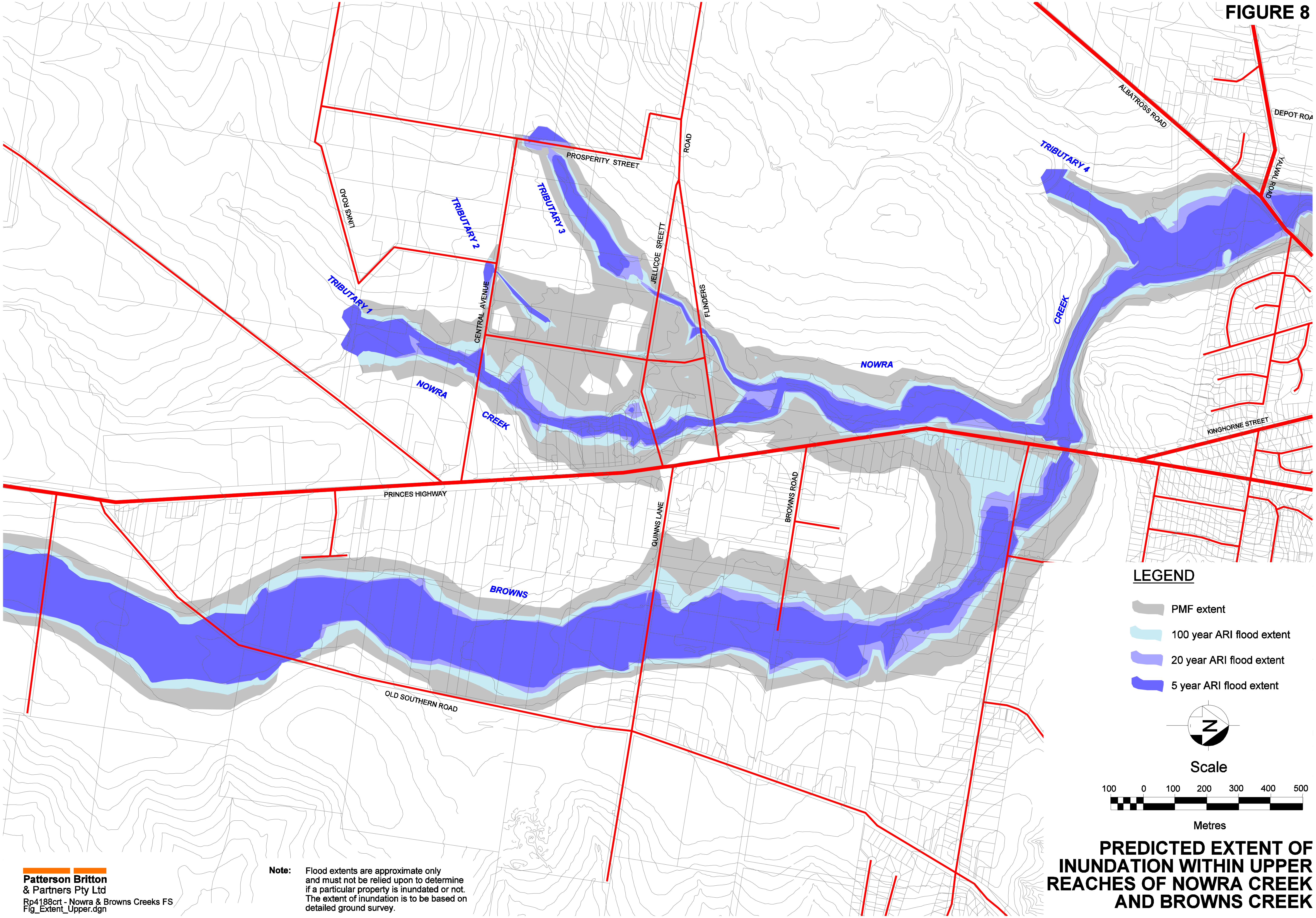
Peak flood levels and velocities for the 5, 20 and 100 year ARI flood events are listed in **Table 19** for each model cross-section along the upper reaches of Nowra Creek. Corresponding results for cross-sections along Browns Creek are listed in **Table 20**. Model results for the lower reaches of Nowra Creek are listed in **Table 21**. Peak flood level and flow velocities for all modelled flood events are provided in **Appendix K.** The predicted extent of inundation in the 100 year ARI flood is shown in **Figures 8** and **9**.

It is important to note that the results reported in this study reflect flood behaviour under current catchment conditions, rather than the fully developed conditions, which will be considered during the subsequent floodplain risk management study for this area, so as to determine appropriate Flood Planning Levels for application to future development in the study area.

Table 19 HYDRAULIC MODEL RESULTS FOR UPPER NOWRA CREEK

CROSS SECTION (*refer Figure 5*)	100 YEAR ARI EVENT				20 YEAR ARI EVENT				5 YEAR ARI EVENT			
	Peak Level (mAHD)	Peak Velocity (m/s)			Peak Level (mAHD)	Peak Velocity (m/s)			Peak Level (mAHD)	Peak Velocity (m/s)		
		Left	Chan	Right		Left	Chan	Right		Left	Chan	Right
N38	34.7	1.0	1.3	1.4	34.0	1.0	1.4	1.7	33.8	0.8	1.2	1.2
N37	33.7	1.0	1.7	1.4	33.2	0.9	1.4	1.2	33.0	0.7	1.3	0.9
N36	32.7	1.2	2.3	1.5	32.2	1.3	2.3	1.2	31.8	0.8	2.2	0.8
N35	32.1	1.1	1.4	1.3	31.5	1.3	1.4	0.9	31.2	1.0	1.2	0.5
N34	31.1	1.5	1.6	1.1	30.5	1.5	1.6	1.3	30.4	1.0	1.4	1.0
N33	30.1	1.1	2.1	1.3	29.2	1.2	2.1	1.2	28.8	0.8	1.7	0.9
N32	29.3	1.1	1.5	1.6	28.7	1.2	1.4	1.5	28.4	0.9	1.4	1.1
N31	28.0	1.0	1.4	1.6	27.3	0.9	1.4	1.6	27.0	0.4	1.3	1.3
N30A	27.1	0.8	0.9	0.7	26.6	0.6	0.7	0.7	26.3	0.5	0.6	0.4
N29	25.4	1.3	0.8	0.3	24.3	1.0	1.0	0.4	23.7	0.8	0.9	0.2
N28	25.4	0.7	0.8	0.9	24.2	0.7	0.9	1.1	23.7	0.6	0.8	0.6
N27A	22.4	1.4	2.0	1.2	21.7	1.5	2.5	1.7	21.4	1.3	1.9	0.8
N27	21.7	1.1	1.4	0.8	21.4	1.0	1.3	0.9	21.0	1.0	1.6	1.1
N24	21.3	1.5	1.3	1.9	21.2	1.6	1.4	1.6	20.6	1.9	1.6	1.7

FIGURE 8



PREDICTED EXTENT OF INUNDATION WITHIN UPPER REACHES OF NOWRA CREEK AND BROWNS CREEK

Note: Flood extents are approximate only and must not be relied upon to determine if a particular property is inundated or not. The extent of inundation is to be based on detailed ground survey.

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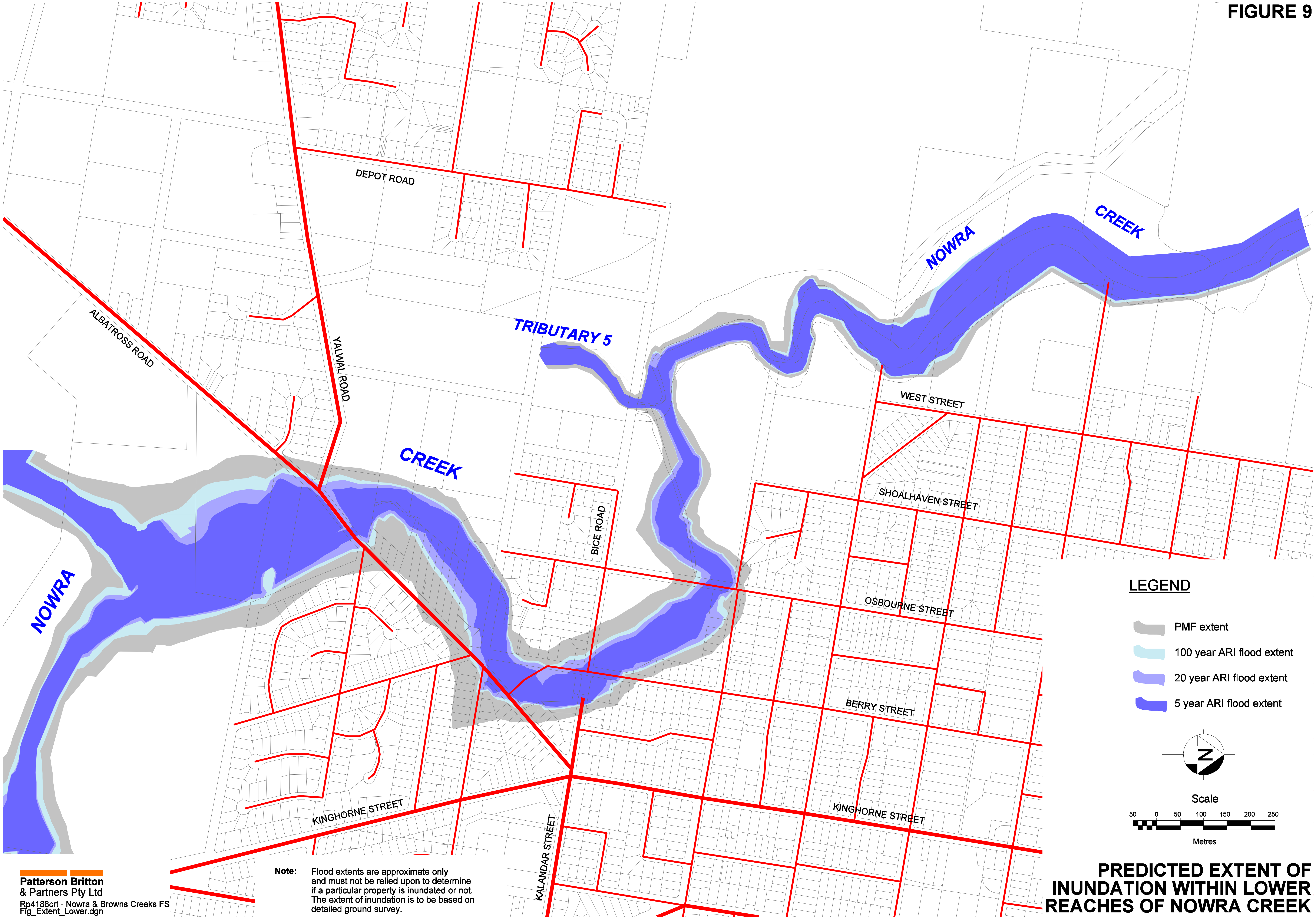
Fig_Extent_Upper.dgn

FIGURE 9



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Fig_Extent_Lower.dgn

Note: Flood extents are approximate only and must not be relied upon to determine if a particular property is inundated or not. The extent of inundation is to be based on detailed ground survey.

PREDICTED EXTENT OF INUNDATION WITHIN LOWER REACHES OF NOWRA CREEK

Table 20 HYDRAULIC MODEL RESULTS FOR BROWNS CREEK

CROSS SECTION (*refer Figure 5*)	100 YEAR ARI EVENT				20 YEAR ARI EVENT				5 YEAR ARI EVENT			
	Peak Level (mAHD)	Peak Velocity (m/s)			Peak Level (mAHD)	Peak Velocity (m/s)			Peak Level (mAHD)	Peak Velocity (m/s)		
		Left	Chan	Right		Left	Chan	Right		Left	Chan	Right
B14	42.6	0.5	1.1	0.5	42.1	0.7	1.4	0.6	42.0	0.4	1.1	0.8
B13	41.7	0.6	1.5	0.6	41.4	0.7	1.3	0.8	41.2	0.4	1.4	1.2
B12	40.3	0.7	1.3	0.7	39.9	1.1	0.8	0.5	39.9	0.5	1.3	0.8
B11	39.3	0.9	1.2	0.9	38.8	1.6	1.0	0.6	38.8	0.8	1.2	0.6
B10	38.8	0.4	0.7	0.4	38.4	0.6	0.3	0.4	38.3	0.4	0.9	0.2
B9	38.2	0.5	1.4	0.5	37.9	0.9	0.5	0.9	37.8	0.3	1.4	0.3
B8	36.5	0.6	1.2	0.6	36.2	0.7	0.6	0.7	36.0	0.3	1.3	0.3
B7	34.4	1.1	1.3	1.1	34.1	0.9	0.8	0.7	34.0	1.0	1.3	0.3
B6	32.5	0.7	0.7	0.7	32.3	0.5	0.9	0.4	32.2	0.2	0.6	0.4
B5	30.3	0.7	0.9	0.7	30.0	0.9	0.3	0.6	30.0	0.3	0.8	0.2
B4	29.3	1.0	1.6	1.0	29.2	1.0	0.4	0.7	28.9	1.0	1.6	0.3
B3	28.4	1.3	1.9	1.3	28.2	1.2	0.9	1.1	27.9	0.9	1.7	0.4
B2	26.0	0.7	1.1	0.7	25.6	0.7	0.9	0.5	25.5	0.4	0.8	0.3
B1	25.5	0.6	1.0	0.6	24.5	0.8	0.8	0.7	23.9	0.8	1.3	1.0

Discussion

The hydraulic modelling results indicate that the lateral extent of flooding along Browns Creek is much more pronounced than along the upper reaches of Nowra Creek. This is associated with the limited flow carrying capacity of the Browns Creek channel. The creek channel invert is generally less than 0.5 metres below the channel bank. Therefore, even during minor flooding, there is a high likelihood that the banks of Browns Creek will be overtopped.

Albatross Road causes a significant "back-up" of floodwaters with the roadway effectively acting as a levee. Floodwaters build-up behind the road embankment and overtop the roadway in events rarer than the 5 year ARI flood.

Similarly, floodwaters travelling along Browns Creek will build up behind the Princes Highway during major events (*i.e. events rarer than the 20 year ARI flood*). Overtopping of the Princes Highway is only predicted to occur during the PMF.

The flood profile shown in **Figure 6** is a 'good fit' to the known flood marks for the 1978 flood. The 1978 flood is approximately half way in between the 20 year and 10 year ARI flood events. The modelled design affluxes across the bridges are supported by the 1978 floodmarks.

Predicted affluxes through bridge crossings of Nowra and Browns Creeks were also verified by applying Bradley's method (*1978*). The results of this analysis are summarised in **Appendix L** for the 100 year ARI flood and indicates that affluxes of in excess of 300 mm are predicted to occur at the Central Avenue, Flinders Road and Albatross Road.

In general, the bridge affluxes predicted by the RMA-2 model agreed to within 50 mm of those predicted using Bradley's method.

Table 21 HYDRAULIC MODEL RESULTS FOR LOWER NOWRA CREEK

CROSS SECTION (*refer Figure 5*)	100 YEAR ARI EVENT				20 YEAR ARI EVENT				5 YEAR ARI EVENT			
	Peak Level (mAHD)	Peak Velocity (m/s)			Peak Level (mAHD)	Peak Velocity (m/s)			Peak Level (mAHD)	Peak Velocity (m/s)		
		Left	Chan	Right		Left	Chan	Right		Left	Chan	Right
N21	21.2	1.2	1.9	1.5	20.8	1.3	1.6	1.3	19.9	1.4	1.7	1.6
N20	20.6	1.4	1.8	1.4	20.2	1.9	1.1	1.2	19.3	0.4	1.9	1.4
N19	20.2	0.8	1.2	0.8	19.9	0.9	0.8	0.8	19.0	1.0	1.5	0.2
N16	19.6	1.3	1.3	1.2	19.3	1.2	1.0	1.4	18.6	0.7	1.4	0.7
N15	19.3	1.1	1.1	1.1	18.9	1.2	0.8	0.7	18.1	0.4	1.5	1.3
N14	19.2	1.4	1.4	1.5	18.8	1.6	1.3	1.3	17.9	0.6	2.0	1.9
N13	18.8	0.6	1.2	1.2	18.4	1.2	0.7	0.9	17.5	0.3	1.1	1.0
N11	17.3	0.7	1.9	1.2	17.0	0.5	1.1	1.5	15.8	0.6	2.1	0.7
N10	16.8	1.6	1.9	1.4	16.6	1.6	1.1	0.9	15.4	1.6	1.9	1.5
N9	14.9	2.6	3.4	2.2	15.0	1.9	2.4	1.5	13.1	3.1	4.1	3.0
N8	14.3	2.0	2.0	2.4	14.1	1.6	1.6	1.5	12.5	2.5	2.5	2.6
N7	11.2	2.5	3.3	2.5	11.2	1.9	2.2	1.8	9.7	3.0	3.3	2.5
N6	8.0	2.3	1.3	1.7	7.3	1.5	0.7	0.9	6.2	3.4	1.4	3.1
N5	7.7	0.8	1.9	1.7	6.7	1.0	1.7	1.5	6.1	0.5	1.7	1.9
N4	7.7	0.5	1.1	0.5	6.5	0.6	0.7	0.5	6.1	0.5	0.6	0.2
N3	7.7	0.4	0.6	0.3	6.5	0.5	0.5	0.4	6.0	0.3	0.3	0.2
N2	7.7	0.3	0.2	0.1	6.5	0.4	0.2	0.1	6.0	0.2	0.1	0.1
N1	7.7	0.3	0.3	0.2	6.5	0.3	0.2	0.2	6.0	0.1	0.2	0.2

6.2.3 Sensitivity Analysis

The development of any hydraulic model requires the adoption of several variables that are not necessarily known with a high degree of certainty (***e.g., roughness parameters***). Accordingly, the model results can vary according to the final values adopted within the model. Therefore, a sensitivity analysis is typically undertaken to determine the reliability of the results generated by the hydraulic model.

Roughness Parameters

As discussed in **Section 5.3.2**, a sensitivity analysis was undertaken to assess the impact of the raising the roughness parameter values for densely vegetated areas of the riparian corridor. This analysis was undertaken for the 1978 flood.

As the 1978 flood is regarded as being between a 10 and 20 year ARI event, a further sensitivity analysis was undertaken to assess the impact that the adopted roughness values would have on peak flood levels during a more severe flood. Since the 1989 flood was not used for verification, the sensitivity analysis was performed for the 100 year ARI design event.

The results of the sensitivity analysis for the 100 year ARI design flood are presented in **Figures J3** and **J4** which are enclosed within **Appendix J**.

The results show an increase in simulated flood levels if roughness values of the order of 0.15 are adopted in these areas. However, the maximum increase in flood level is only 200 mm and increases of this magnitude are generally restricted to areas of Crown Land or State Forest (***i.e.,*** *the densely vegetated areas likely to have vegetation density consistent with roughness parameter values of 0.15*). Increases in simulated flood levels in urbanised areas were found to be less than 100 mm.

Tailwater Levels

Similarly, a sensitivity check was performed on the adopted tailwater levels for the 100 year ARI design flood event. Reducing the tailwater level by 10% influenced flood levels from the confluence of Nowra Creek and the Shoalhaven River upstream for a distance of around 1,500 m. Upstream of this, flood levels remained unchanged. Similar results were experienced when increasing the tailwater level by 10%. Therefore, the adopted tailwater level does not impact on flood levels within the developed regions of the catchment.

6.2.4 Probable Maximum Flood

The probable maximum flood (*PMF*) is the largest flood that could conceivably occur at a particular location. Although floods of this magnitude are extreme, they are important for several reasons.

Firstly they define the total extent of the floodplain or to put it another way the total area to which the NSW Government's Flood Prone Land Policy applies in the catchment. Secondly the PMF provides important criteria for consideration in the subsequent floodplain risk management study of the catchment when appropriate risk management measures and the acceptability of the residual flood risk will be assessed.

For example, the PMF should be considered when identifying the location of resources that are critical during floods, such as telephone exchanges, police stations and hospitals. The PMF is also important for contingency planning for the safety of people on the floodplain as well as for assessment of Flood Hazard and Flood Planning Levels.

These issues will need to be considered in detail during the subsequent floodplain risk management study for this area. In recognition of these factors, investigations were undertaken to assess the magnitude of the PMF and its potential impact on the Nowra and Browns Creeks study area.

Probable Maximum Precipitation

Estimates of the probable maximum flood should be based on the probable maximum precipitation (*PMP*). The PMP is defined as the greatest depth of precipitation that is meteorologically possible for a given duration at a specific location at a particular time of year.

Procedures for estimation of the PMP are outlined in a document published by the Bureau of Meteorology, which is titled, *'Bulletin 53 - The Estimation of Probable Maximum Precipitation in Australia: Generalised Short-Duration Method'* (*1994*). These procedures were applied to the Nowra and Browns Creeks catchment to derive the PMP for Nowra.

Current procedures for determination of the PMP for small catchments are based on a method known as the *'Generalised Short-Duration Method'* (*GSDM*). Application of procedures for this method indicates that a 3 hour storm duration should be adopted for the Nowra and Browns Creek catchment.

For this duration, the Probable Maximum Precipitation is estimated to be 480 mm. That is, for a PMF event to occur at Nowra, it is estimated that 480 mm of rainfall must fall on the catchment over a three hour period. In comparison, the total rainfall predicted for a 100 year ARI storm of 3 hour duration is estimated to be 172 mm (*3 x 57.2 mm/hr - refer* **Appendix G**).

A design temporal distribution of the short-duration PMP was also determined in accordance with procedures outlined in *Bulletin 53*. The temporal pattern was based on a standard mass curve which provided total rainfalls over each 9 minute period in the 3 hour storm duration. This was used in the RAFTS hydrologic model to simulate runoff processes in the Nowra Creek catchment for the PMP event.

Probable Maximum Flood Levels

The peak discharge for the PMF in the Nowra and Browns Creeks catchment was determined by applying the temporally distributed PMP in the RAFTS hydrologic model. As the catchment area is only 20 km^2, spatial distribution of the rainfall was not considered in the modelling.

It was also assumed that the antecedent wetness conditions in the catchment corresponded to the same conditions that were adopted for the other design storm events.

Modelling indicates a peak PMF discharge of 1131 m^3/s at the downstream end of the Nowra and Browns Creeks catchment. Estimates of peak flood levels for the PMF are presented in **Tables 22**, **23** and **24**. The peak 100 year ARI flood levels are also provided for comparison.

Table 22 PREDICTED PEAK FLOOD LEVELS FOR UPPER NOWRA CREEK

CROSS-SECTION (*refer Figure 5*)	PEAK LEVEL (*mAHD*)	
	100 Year ARI Event	Probable Maximum Flood
N38	34.7	36.1
N37	33.7	35.0
N36	32.7	33.9
N35	32.1	33.2
N34	31.1	32.6
N33	30.1	31.6
N32	29.3	31.1
N31	28.0	29.7
N30A	27.1	28.6
N29	25.4	28.3
N28	25.4	28.2
N27A	22.4	24.0
N27	21.7	23.4
N24	21.3	22.9

Table 23 PREDICTED PEAK FLOOD LEVELS FOR LOWER NOWRA CREEK

CROSS-SECTION (*refer Figure 5*)	PEAK LEVEL (*mAHD*)	
	100 Year ARI Event	Probable Maximum Flood
N21	21.2	22.9
N20	20.6	22.5
N19	20.2	22.1
N16	19.6	21.7
N13	19.3	21.5
N11	19.2	21.4
N10	18.8	21.1
N9	17.3	20.1
N8	16.8	19.6
N7	14.9	17.8
N6	14.3	17.0
N5	11.2	14.0
N4	8.0	12.2
N3	7.7	11.5
N2	7.7	11.4
N1	7.7	11.3

Table 24 PREDICTED PEAK FLOOD LEVELS FOR BROWNS CREEK

CROSS-SECTION (*refer Figure 5*)	PEAK LEVEL (*mAHD*)	
	100 Year ARI Event	Probable Maximum Flood
B14	42.6	43.4
B13	41.7	42.5
B12	40.3	41.1
B11	39.3	40.2
B10	38.8	39.7
B9	38.2	38.9
B8	36.5	37.3
B7	34.4	35.0
B6	32.5	33.1
B5	30.3	31.0
B4	29.3	30.0
B3	28.4	29.3
B2	26.0	28.5
B1	25.5	28.4

7 PROVISIONAL FLOOD HAZARD CATEGORISATION

7.1 FLOOD HAZARD

The personal danger and physical property damage caused by a flood varies both in time and place across the floodplain. Accordingly, the variability of flood patterns across the floodplain over the full range of floods needs to be understood by flood prone landholders and by floodplain managers.

Representation of the variability of flood hazard across the floodplain provides floodplain risk managers with a tool to assess the existing flood risk during the floodplain risk management study. This allows them to then determine the suitability of particular land uses across the floodplain so as to determine the appropriate land use zonings and controls to apply to future development.

The Hydraulic and Hazard categorisation of flood prone land is discussed in Appendix G of the Floodplain Management Manual (2001). It takes into consideration a range of matters not considered in the analyses carried out in flood studies. The matters considered in flood studies produce information suitable for identification of hydraulic categories and provisional hazard categories for different parts of the floodplain.

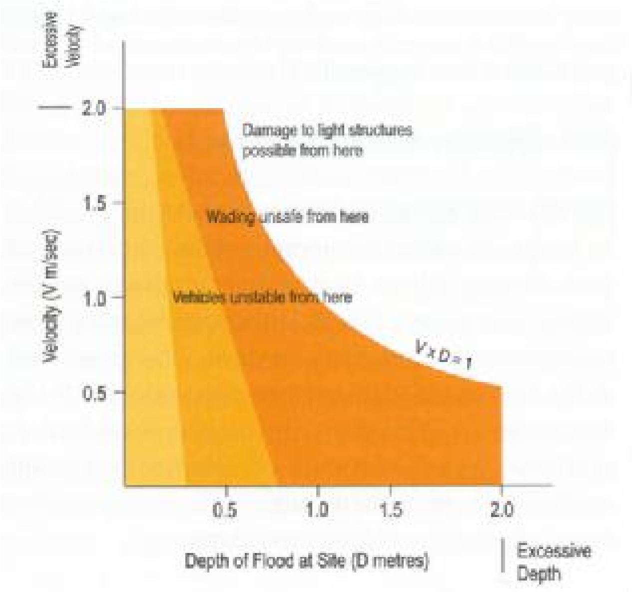
The NSW Government's *'Floodplain Management Manual'* (*2001*), characterises hazards associated with flooding into a combination of three hydraulic categories and two hazard categories. The three hydraulic categories are Floodways, Flood storage areas and Flood fringe. Hazard categories are then assigned as high and low hazard for each hydraulic category as follows:

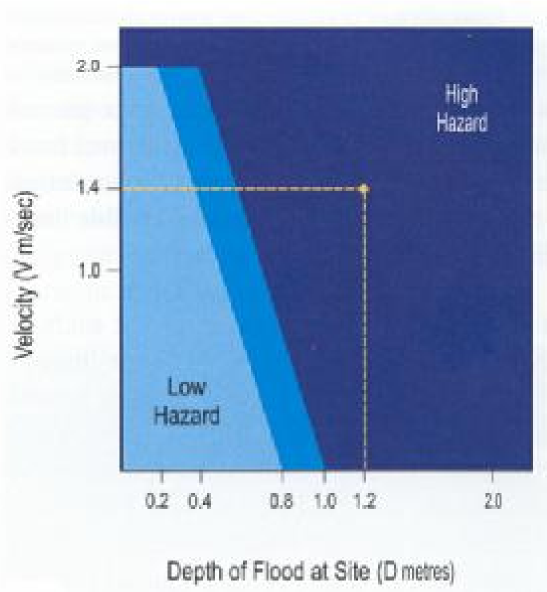
- Low Hazard – Flood Fringe
- Low Hazard – Flood Storage
- Low Hazard – Floodway
- High Hazard – Flood Fringe
- High Hazard – Flood Storage
- High Hazard - Floodway

The hydraulic category is determined by consideration of aspects of flood behaviour such as whether the area is a significant flow path, storage area or is just on the fringes of the flood. The provisional hazard category in a particular location associated with a given flood is determined from the static and dynamic energy of the flow, which is the depth and velocity of the floodwaters.

Therefore, the provisional flood hazard at a particular location within the floodplain is a function of the depth and flow velocity of the floodwaters at that location.

As a result, the flood behaviour is categorised using the six categories, outlined above. An interpretation of the provisional flood hazard at a particular part of a floodplain can be established from the following graphs, which have been taken directly from the manual.





The first of these graphs shows approximate relationships between the depth and velocity of floodwaters and resulting outcomes such as "Vehicles unstable from here", "Wading unsafe from here" and "Damage to light structures possible from here". Consideration of these outcomes has been used to inform the allocation of provisional low and high hazard categories to the velocity times depth products represented in the second of these plots.

7.2 PROVISIONAL FLOOD HAZARD AND HYDRAULIC CATEGORIES

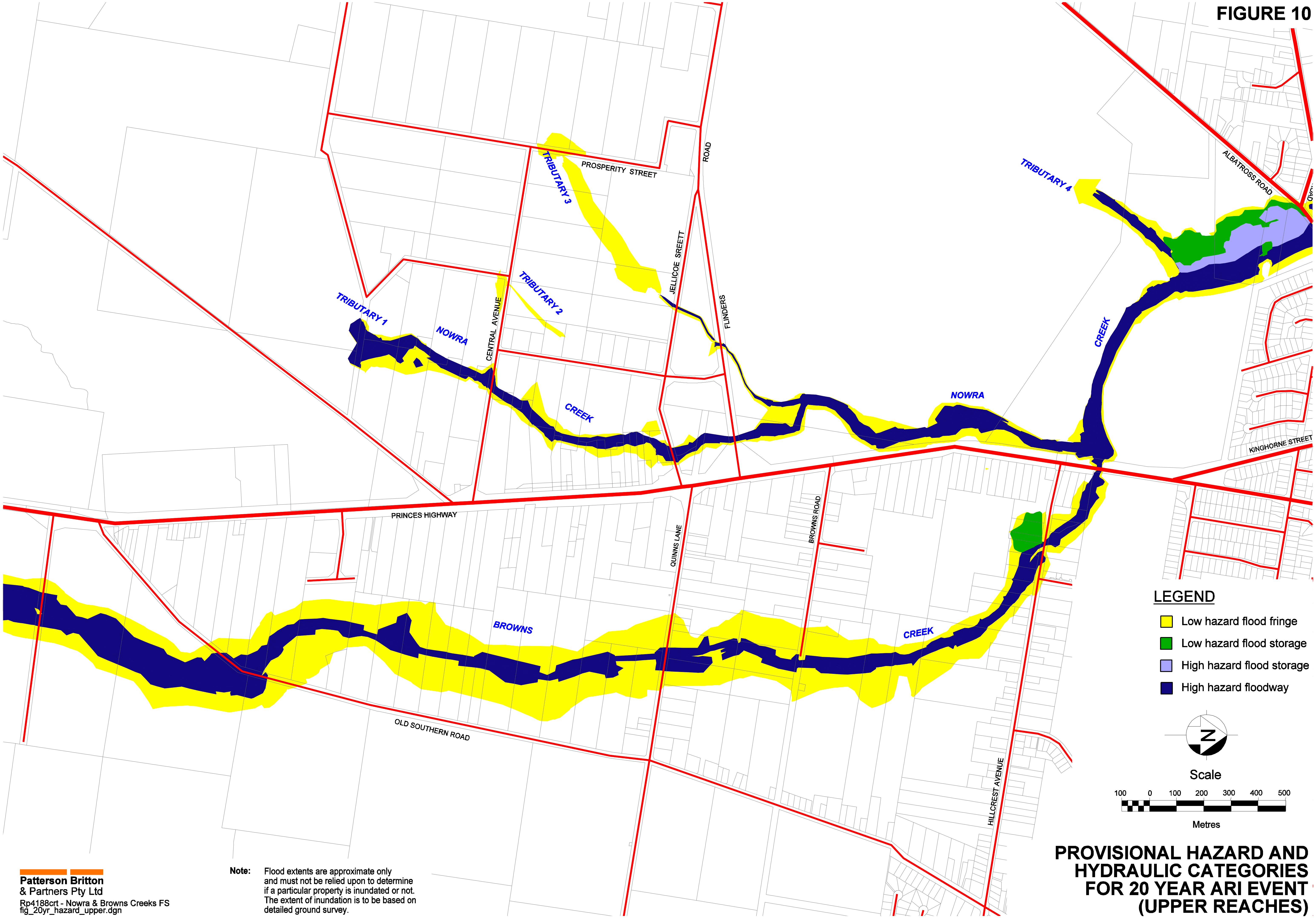
The criteria from the Floodplain Management Manual (2001) were used to determine provisional flood hazard mapping for the Nowra and Browns Creeks floodplain. Results from the computer modelling completed for this study were combined with the hazard category criteria to generate provisional flood hazard and hydraulic categories for the 20, 100 and 500 year ARI floods as well as the PMF. These categories are shown in **Figures 10** to **17**. The limit of the low hazard flood fringe area effectively defines the flood extent for each of these floods.

The hazard represented in this mapping is provisional only. This is because it is based only on an interpretation of the flood hydraulics and does not reflect the effects of other factors that influence flood hazard.

For example, the impacts associated with areas of very high hazard may be reduced if an effective local flood plan is developed, implemented and maintained under the guidance of the State Emergency Services or an area of low provisional hazard may increase to high hazard if it is isolated prior to inundation.

Alternatively, the remoteness of a low hazard area to the edge of the floodplain may mean that the risk to life is greater than originally determined based on hydraulic considerations. If evacuation cannot be safely effected, these areas are likely to be re-classified as high hazard areas.

FIGURE 10



PROVISIONAL HAZARD AND HYDRAULIC CATEGORIES FOR 20 YEAR ARI EVENT (UPPER REACHES)

Note: Flood extents are approximate only and must not be relied upon to determine if a particular property is inundated or not. The extent of inundation is to be based on detailed ground survey.

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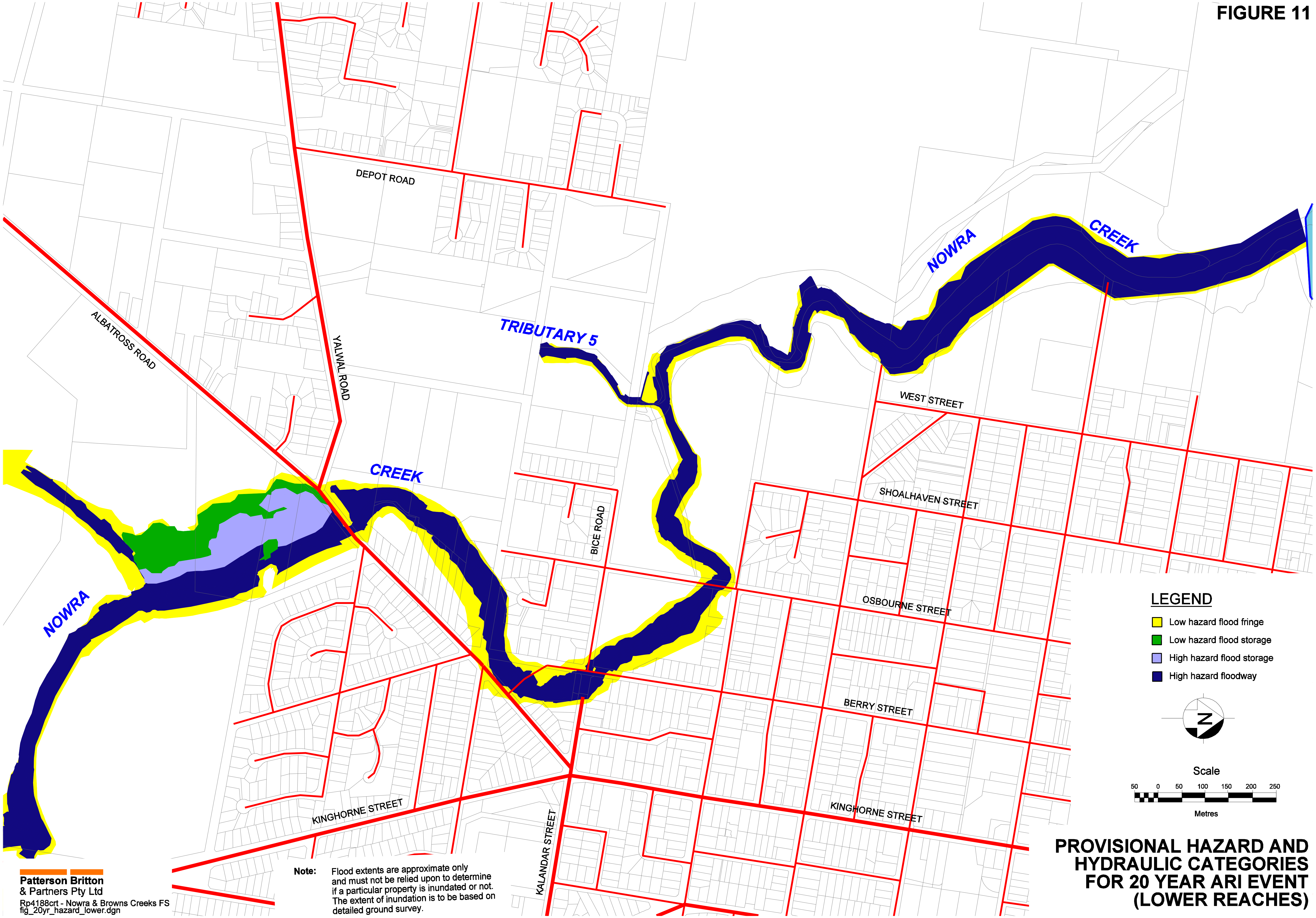
fig_20yr_hazard_upper.dgn

FIGURE 11



PROVISIONAL HAZARD AND HYDRAULIC CATEGORIES FOR 20 YEAR ARI EVENT (LOWER REACHES)

Note: Flood extents are approximate only and must not be relied upon to determine if a particular property is inundated or not. The extent of inundation is to be based on detailed ground survey.

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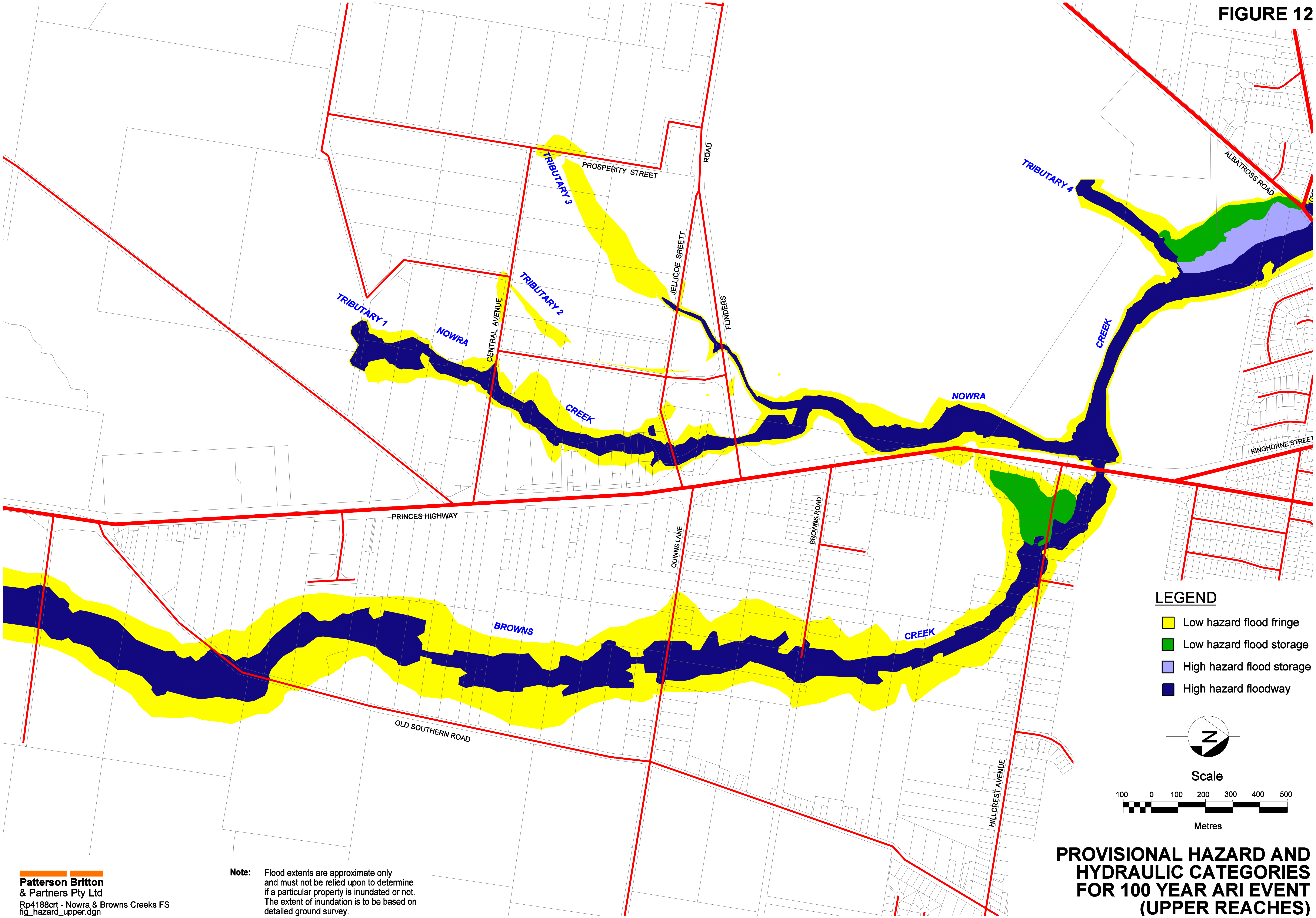
fig_20yr_hazard_lower.dgn

FIGURE 12



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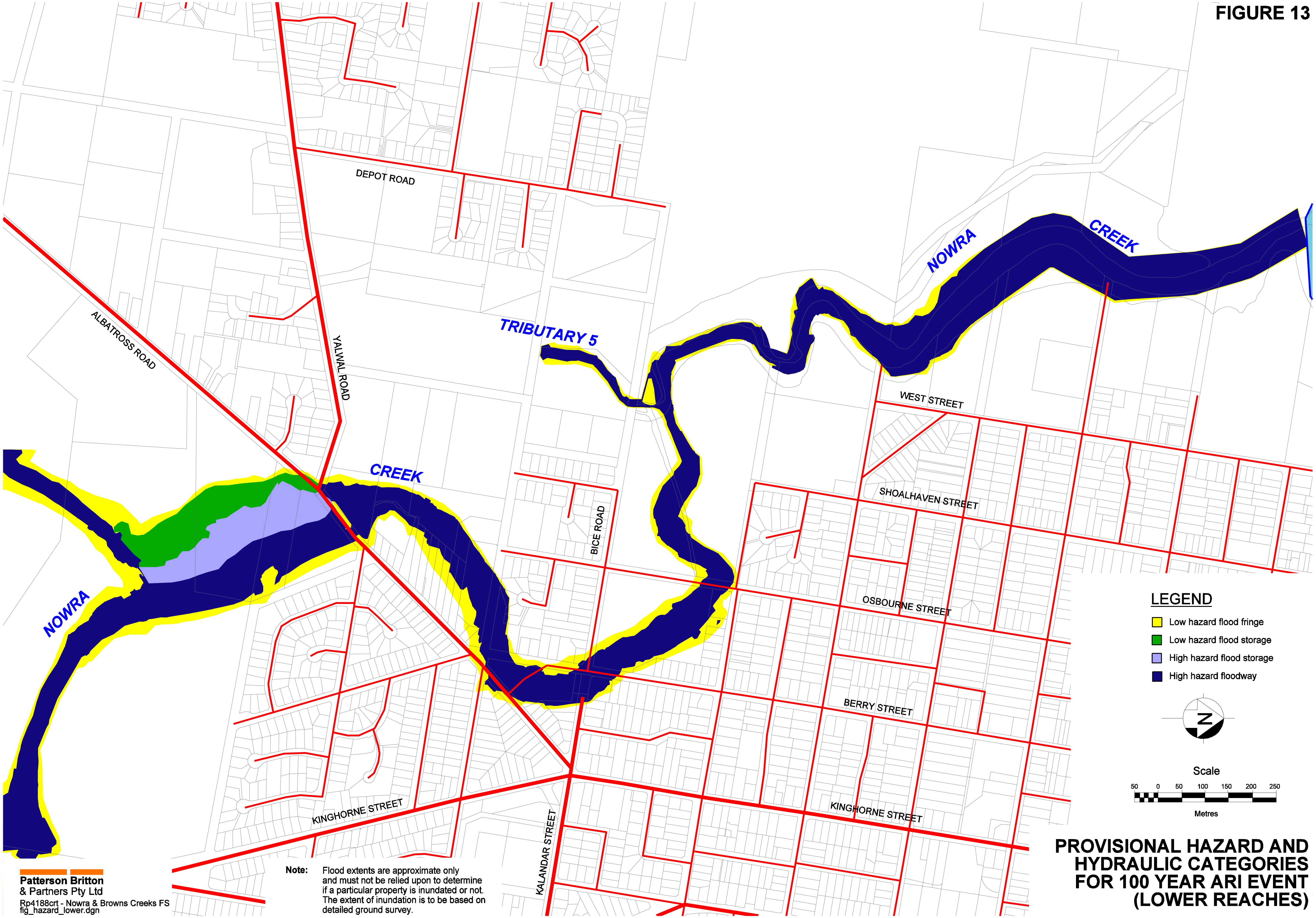
fig_hazard_upper.dgn

Note: Flood extents are approximate only and must not be relied upon to determine if a particular property is inundated or not. The extent of inundation is to be based on detailed ground survey.

PROVISIONAL HAZARD AND HYDRAULIC CATEGORIES FOR 100 YEAR ARI EVENT (UPPER REACHES)

FIGURE 13



LEGEND

- Low hazard flood fringe
- Low hazard flood storage
- High hazard flood storage
- High hazard floodway

PROVISIONAL HAZARD AND HYDRAULIC CATEGORIES FOR 100 YEAR ARI EVENT (LOWER REACHES)

Note: Flood extents are approximate only and must not be relied upon to determine if a particular property is inundated or not. The extent of inundation is to be based on detailed ground survey.

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