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YARROWLUMLA SHIRE COUNCIL

BUNGENDORE FLOOD STUDY

Issue No. 3
NOVEMBER 2002

Document Amendment and Approval Record

Issue	Description of Amendment	Prepared by [date]	Verified by [date]	Approved by [date]
1	Issue for Review	TKH	David McConnell	
2	Final Report	TKH	DMC	
3	Updated Final Report (*incorporating revised cadastre and modelling results*)	CRT	DJT	Chris Thomas (*30/11/02*)

Note: This document is preliminary unless it is approved by a principal of Patterson Britton & Partners.

Document Reference: **rp2722crt021130-Bungendore FS**
Time and Date Printed: **11:35 am 30th November 2002**

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FOREWORD

The State Government's Flood Policy is directed towards 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 defined in the Government's Floodplain Development Manual.

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

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

STAGES OF FLOODPLAIN MANAGEMENT

STAGE		DESCRIPTION
1	**Flood Study**	Determines the nature and extent of the flood problem.
2	**Floodplain Management Study**	Evaluates management options for the floodplain in respect of both existing and proposed developments.
3	**Floodplain Management Plan**	Involves formal adoption by Council of a plan of management for the floodplain.
4	**Implementation of the Plan**	Construction of flood mitigation works to protect existing development. Use of environmental plans to ensure new development is compatible with the flood hazard.

A detailed description of the inter-relationship between these stages is provided overleaf. The link between the various outcomes of the studies involved in the floodplain management process and the implementation of measures to reduce flood damages (*both planning and structural*), is also shown.

Yarrowlumla Shire Council commenced this process in 1997, when it formed the Yarrowlumla Floodplain Management Committee. Council and the Committee, with the technical and financial support of the NSW Department of Land & Water Conservation, have proceeded with the floodplain management process by commissioning this flood study.

The Bungendore Flood Study represents the first of the four stages. It has been prepared to assist Yarrowlumla Shire Council and the local community to understand and define the existing flood behaviour and to establish the basis for the implementation of floodplain management measures.

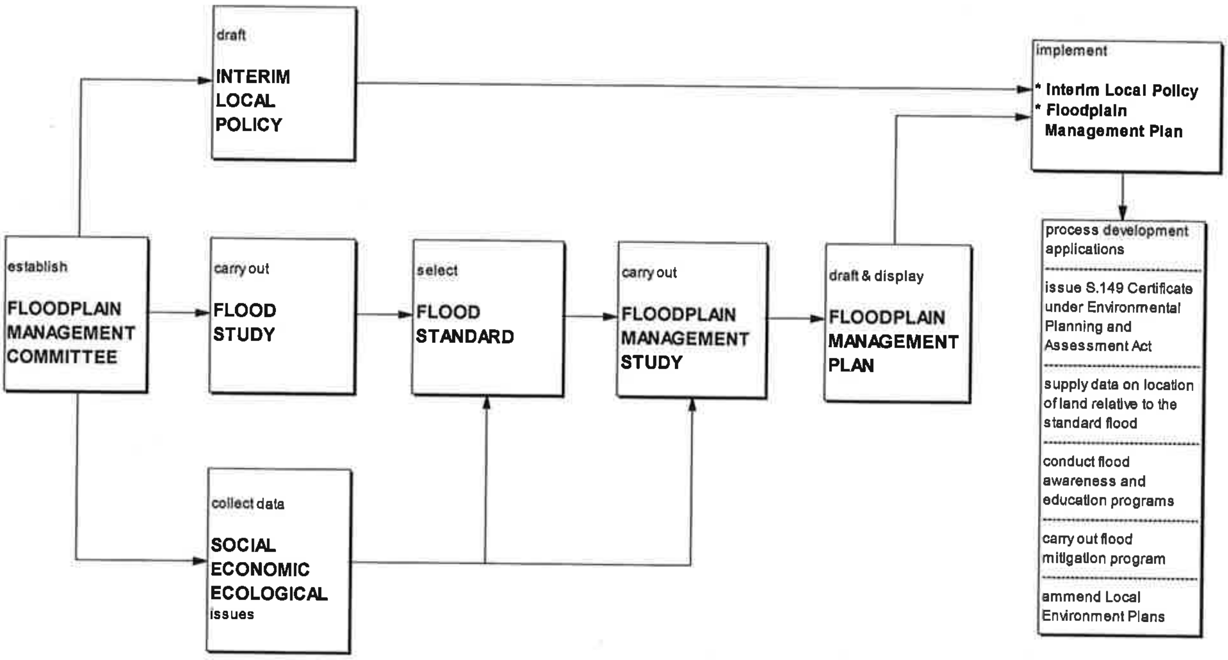

draft
INTERIM LOCAL POLICY
implement
* Interim Local Policy
* Floodplain Management Plan
establish
FLOODPLAIN MANAGEMENT COMMITTEE
carry out
FLOOD STUDY
select
FLOOD STANDARD
carry out
FLOODPLAIN MANAGEMENT STUDY
draft & display
FLOODPLAIN MANAGEMENT PLAN
process development applications
issue S.149 Certificate under Environmental Planning and Assessment Act
supply data on location of land relative to the standard flood
conduct flood awareness and education programs
carry out flood mitigation program
ammend Local Environment Plans
collect data
SOCIAL ECONOMIC ECOLOGICAL issues

TABLE OF CONTENTS

Page No.

TABLE OF CONTENTS

Page No.

TABLE OF CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

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.
Australia Height Datum (AHD)	A common national survey 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. The ARI is another way of expressing the likelihood of occurrence of a flood event.
catchment	The catchment at a particular point is the area of land which drains to that point.
design floor level	The minimum (*lowest*) floor level specified for a building.
design flood	A hypothetical flood representing a specific likelihood of occurrence (*for example the 100 year or 1% annual exceedance probability flood*). The design flood may comprise two or more single source dominated floods.
development	Existing or proposed works which may or may not impact upon flooding. Typical works are filling of land and the construction of roads, floodways and buildings.
discharge	The rate of flow of water measured in terms of volume per unit time, for example cubic metres per second. It is not the velocity of flow, which is a measure of how fast water is moving. Rather, it is a measure of how much water is moving. Discharge and flow are interchangeable terms.
effective warning time	The time available after receiving advice of an impending flood and before floodwaters prevent appropriate flood response actions being undertaken.
flash flood	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.
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 threats and consequences of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.
flood frequency analysis	An analysis of historical flood records to determine estimates of design flood flows.
flood fringe areas	Land which may be affected by flooding but is not designated as a floodway or flood storage.
flood hazard	The potential threat to property or persons due to flooding.
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. Floodplains are a natural formation created by the deposition of sediment during floods.
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. Selection should be based on an understanding of the full range of flood behaviour and the associated flood risk. It should also take into account the social, economic and ecological consequences associated with floods of different severities. The concept of FPL's supersedes the "standard flood event" referred to in the 1986 edition of the *'Floodplain Development Manual'*. FPL's do not define the extent of flood prone land, and floodplain risk management plans must always consider that there is flood prone land above the area defined by an adopted FPL.
flood proofing	Measures taken to improve or modify the design, construction and alteration of buildings to minimise or eliminate flood damages and threats to life and limb.
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 the existing, future and continuing risk.

flood storage areas	Floodplain areas which are important for the temporary storage of floodwaters during the passage of a flood.
floodway areas	Those areas of the floodplain where a significant discharge of water occurs during floods. 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. 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, such as wave action, localised hydraulic effects and impacts that are specific event related (*eg., levee settlement*). Freeboard is included in the flood planning level.
hazard	A source of potential harm or situation with a potential to cause loss. Flood hazard is the potential for flooding to cause damage to the community.
historical flood	A flood which has actually occurred.
hydraulics	The term given to the study of water flow in rivers, estuaries and coastal systems. It is particularly applied to the evaluation of flow parameters such as water level and velocity.
hydrograph	A graph showing how the discharge or flood level changes with time.
hydrology	The term given to the study of the rainfall and runoff process in catchments.
local overland flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary or lake.
mainstream flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary or lake.
mathematical / computer models	The mathematical representation of the physical processes involved in runoff generation and stream flow.
minor flooding	Causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower level of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded.
moderate flooding	Low lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered.

major flooding	Appreciable extents of urban areas are covered and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.
peak discharge	The maximum discharge or flow occurring during a flood event.
probable maximum flood (PMF)	The largest flood that could conceivably occur at a particular location. It is usually estimated from the probable maximum precipitation. The PMF defines the extent of flood prone land; that is, the floodplain.
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.
probability	A statistical measure of the likely frequency or occurrence of flooding.
runoff	The amount of rainfall from a catchment which actually ends up as flowing water in the river or creek.
stage	Equivalent to "water level". Both are measured with reference to a specified datum.
stage hydrograph	A graph that shows how water level changes with time during a flood.
velocity	The speed at which the flood waters are moving. Typically, modelled velocities in a river or creek are quoted as the depth and width averaged velocity, ie. the average velocity across the whole river or creek section.
water surface profile	A graph showing the flood stage at a given location along a watercourse at a particular time.

1 INTRODUCTION

Bungendore is a small village located close to the New South Wales / Australian Capital Territory border, about 40 kilometres north east of Canberra. It has a population of about 1,850 (*2000 Census*) and is the major urban centre within Yarrowlumla Shire. The town comprises two major precincts, namely, the "village" of Bungendore and the residential Bungendore North. Bungendore North comprises Elmslea East and Elmslea West, which are separated by Tarago Road.

The village is situated on the banks of Turallo Creek immediately upstream from the confluence of Turallo and Halfway Creeks (*refer* **Figure 1**). Millpost Creek joins Turallo Creek less than 1 kilometre downstream of the village. All three streams drain to Lake George, which is located about 7 kilometres downstream of the village.

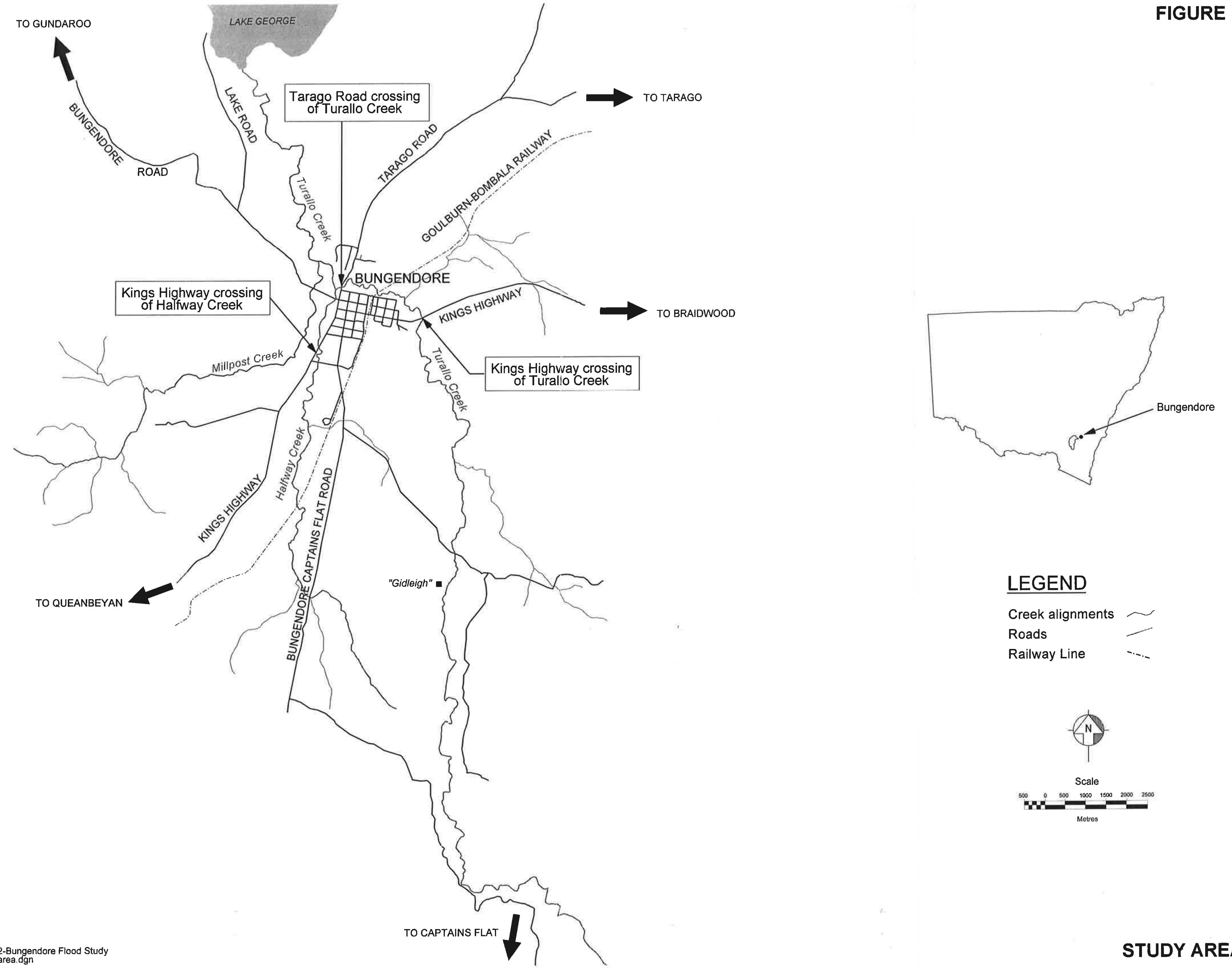
Anecdotal evidence and records of historical floods indicate that a large part of the commercial district of Bungendore is affected by flooding. Flooding in the village occurs primarily as a result of the overtopping of Turallo Creek. However, flows from Halfway and Millpost Creeks can also cause flooding, particularly in the western area of the village (*refer* **Figure 1**).

Although Bungendore is not flooded frequently, severe flooding has occurred on a number of occasions over the last 60 years (*eg., 1956*). In some cases this flooding has led to inundation of low lying areas of the town, causing significant damage to public and private property.

In recognition of the NSW Government's *Flood Prone Lands Policy*, Yarrowlumla Shire Council aims to reduce flood damages experienced by those living in the village. With the support of the NSW Department of Land & Water Conservation (*DLWC*), Council proposes to proceed with the preparation of a floodplain management plan for the village. The floodplain management plan will specify measures and works aimed at reducing flood damages.

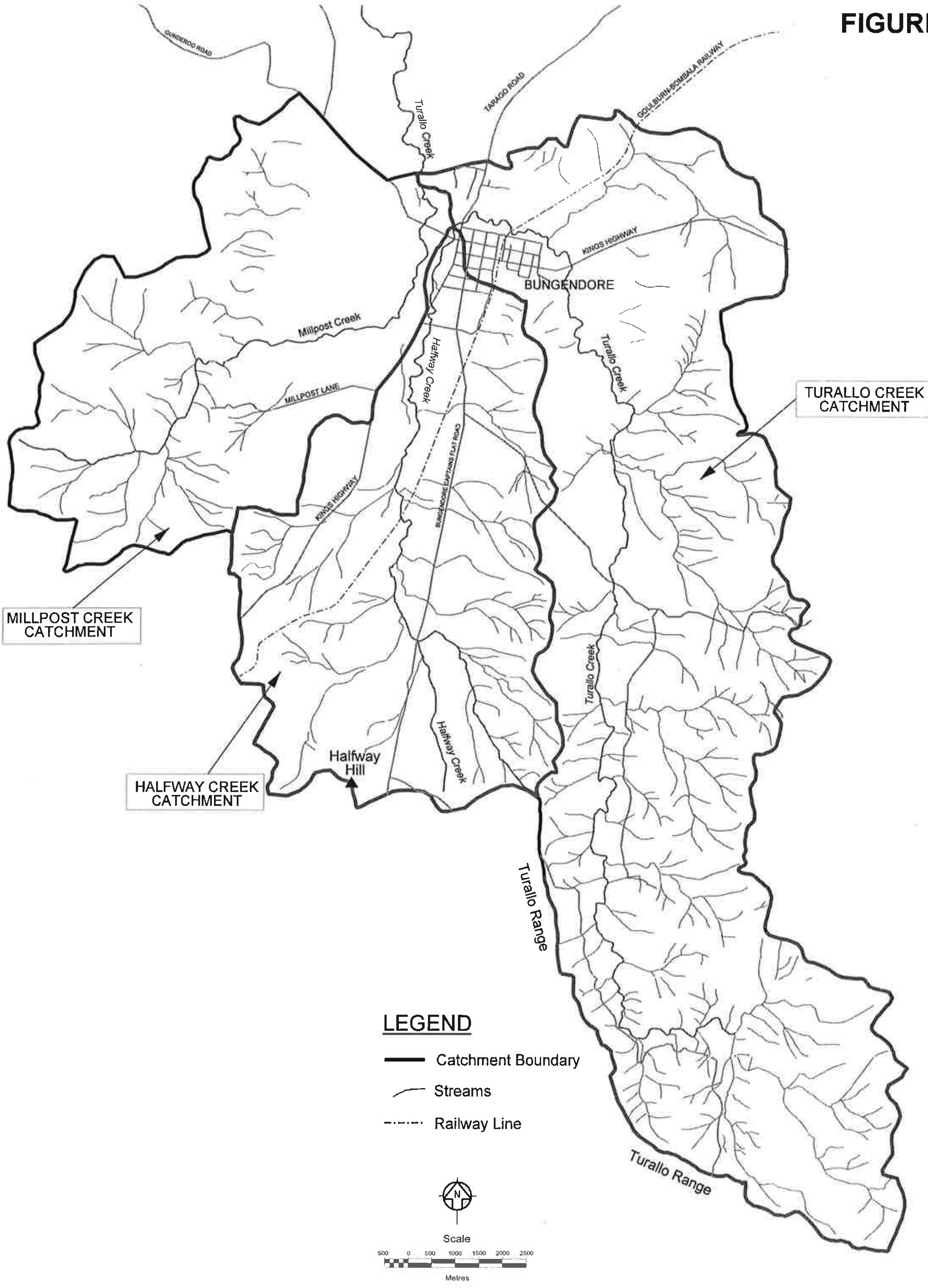
In order to develop the floodplain management plan, it is necessary to have a clear understanding of flood behaviour through the village area. Although two previous flood investigations have been undertaken, neither of these covered the full extent of flood liable land within the recently revised village boundaries. Accordingly, Council determined that there was a need to prepare an updated *Flood Study* based on as much new knowledge and data as possible.

This report documents the findings of the *Flood Study*. It defines flood flows, velocities and peak flood levels for the full range of flood events under existing catchment and floodplain conditions. It also specifies the flood extent for a range of flood severities.


TO GUNDAROO
LAKE GEORGE
LAKE ROAD
BUNGENDORE ROAD
Tarago Road crossing of Turallo Creek
TARAGO ROAD
TO TARAGO
GOULBURN-BOMBALA RAILWAY
Turallo Creek
BUNGENDORE
Kings Highway crossing of Halfway Creek
KINGS HIGHWAY
TO BRAIDWOOD
Millpost Creek
Kings Highway crossing of Turallo Creek
Halfway Creek
KINGS HIGHWAY
BUNGENDORE CAPTAINS FLAT ROAD
"Gidleigh"
TO QUEANBEYAN
TO CAPTAINS FLAT
Bungendore
LEGEND
Creek alignments
Roads
Railway Line
N
Scale
500 0 500 1000 1500 2000 2500
Metres

STUDY AREA

FIGURE 2



CATCHMENT DELINEATION

2 HISTORY OF FLOODING

2.1 DESCRIPTION OF THE CATCHMENT

Turallo, Halfway and Millpost Creeks drain a combined catchment area upstream of Bungendore of about 170 km^2 (*refer* **Figure 2**). All three creeks are ephemeral streams and in dry periods only hold water in local billabongs along their main channel. Nonetheless, during storms, runoff is concentrated in these channels and can overtop the creek banks and flood the village.

Turallo Creek is the major catchment tributary, effectively draining the catchment to Lake George. It rises in the Turallo Range, which is located about 20 kilometres south of Bungendore and extends to an elevation of about 1,000 metres above sea level. The area of the Turallo Creek catchment above the Tarago Road crossing (*refer* **Figure 1**) is about 87 km^2.

Millpost and Halfway Creeks drain smaller catchments and discharge to Turallo Creek immediately downstream of the village. Millpost Creek rises in a range of steep hills located about 10 kilometres south-west of Bungendore. It drains a catchment area of 38 km^2. Halfway Creek flows in a northerly direction from Halfway Hill. Its catchment is located immediately west of the Turallo Range, and covers an area of 41 km^2.

The majority of the catchments of all three creeks have been cleared of riparian vegetation. The land is now used for grazing livestock and some cropping. In their lower reaches, the floodplains of Millpost and Halfway Creeks are extremely flat. In the vicinity of Bungendore, it is difficult to distinguish high ground separating the floodplains of these creeks.

Millpost and Halfway Creeks comprise relatively narrow and shallow channels, extending to typical widths of 5 and 8 metres, respectively. Upstream of its crossing with MR 51 (*refer* **Figure 1**), the channel of Halfway Creek is merely a depression in a broad flat grass covered floodplain. Millpost Creek is not easily definable in the area downstream of the hills in which it rises, where it spreads out over a flat grassy floodplain. About 3 kilometres upstream of Bungendore, it reforms as a well defined channel that extends to its confluence with Turallo Creek.

In floods, the majority of the flow from both the Millpost and Halfway Creek catchments is carried overland across their flat floodplains.

Turallo Creek is more incised, with typical channel depths and widths through the village area of 1.5 and 5 metres, respectively. The lower reaches of Turallo Creek and its contributing catchment from *"Gidleigh"* homestead to Bungendore are flatter, which encourages broader and slower moving flood flows. Accordingly, Turallo Creek is characterised by a meandering channel in the reaches adjacent to Bungendore.

Downstream of Bungendore, Turallo Creek flows in a north-westerly direction to Lake George with only minor lateral inflows from areas directly adjacent to the creek.

2.2 MAJOR FLOODS

Flooding in Bungendore has occurred on numerous occasions since European settlement of the area in the 1850s. In many of these events, floodwaters have overtopped the creek banks and caused inundation of a large proportion of the business district of the village and adjoining residential areas.

Over the last 100 years, floods have occurred in 1904, 1934, 1950, 1956, 1961, 1969, 1974, 1988, and 1991. The major floods to have occurred at Bungendore are those that occurred in:

- 1948;
- June 1956;
- 1974; and,
- 1988.

An example of the extent of flooding in the 1974 flood is shown on the front cover of this report. Severe flooding in 1956 is shown below in **Plate 1**. Less severe flooding is presented in **Plates 2** to **5**, for the July 1991 flood.

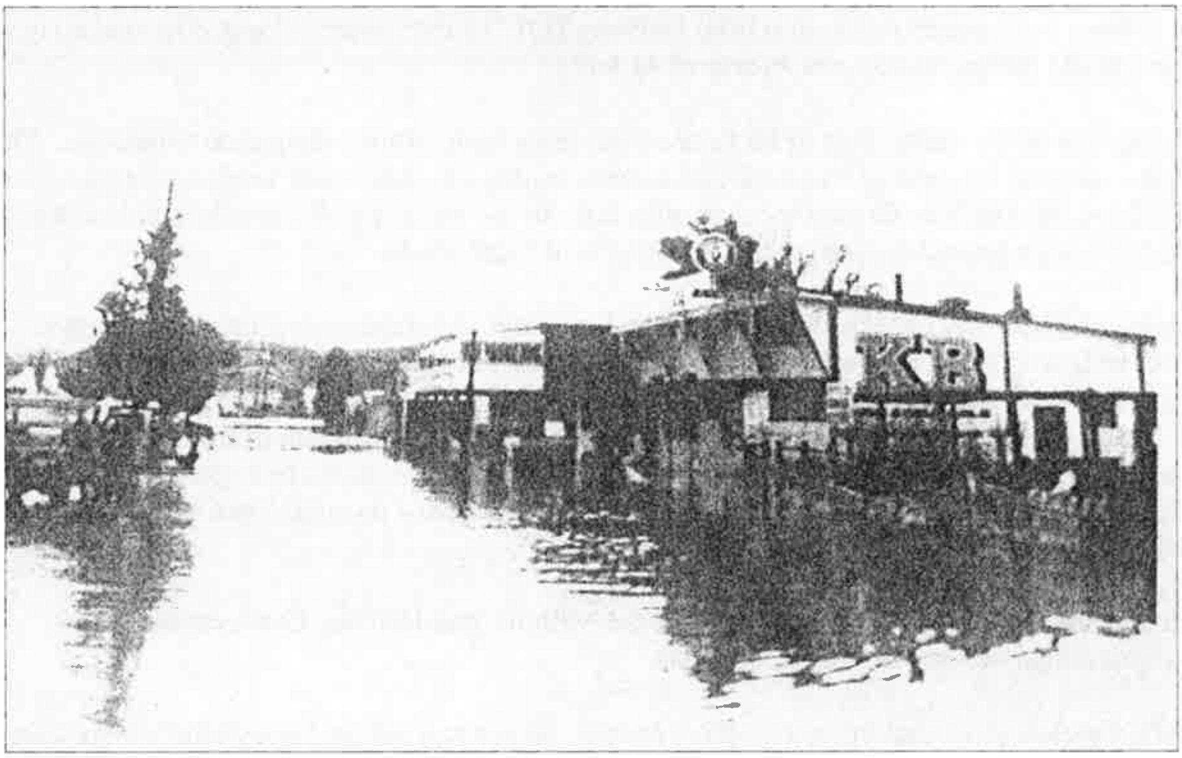


Plate 1: View looking west along Gibralter Street during the 1988 flood and showing the Lake George Hotel in the foreground.

Plate 2 : MAIN ROAD 51 – Bungendore Floodplain at Willow Tree Crossing looking towards Queanbeyan.

Plate 3 : MAIN ROAD 51 – Bungendore Floodplain, upstream side of new 8 cell culvert

Plate 4 : TURALLO CREEK – Upstream, looking east.

Plate 5 : TURALLO CREEK – Downstream, looking west.

3 METHODOLOGY

3.1 BACKGROUND

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 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 management plan that ensures:

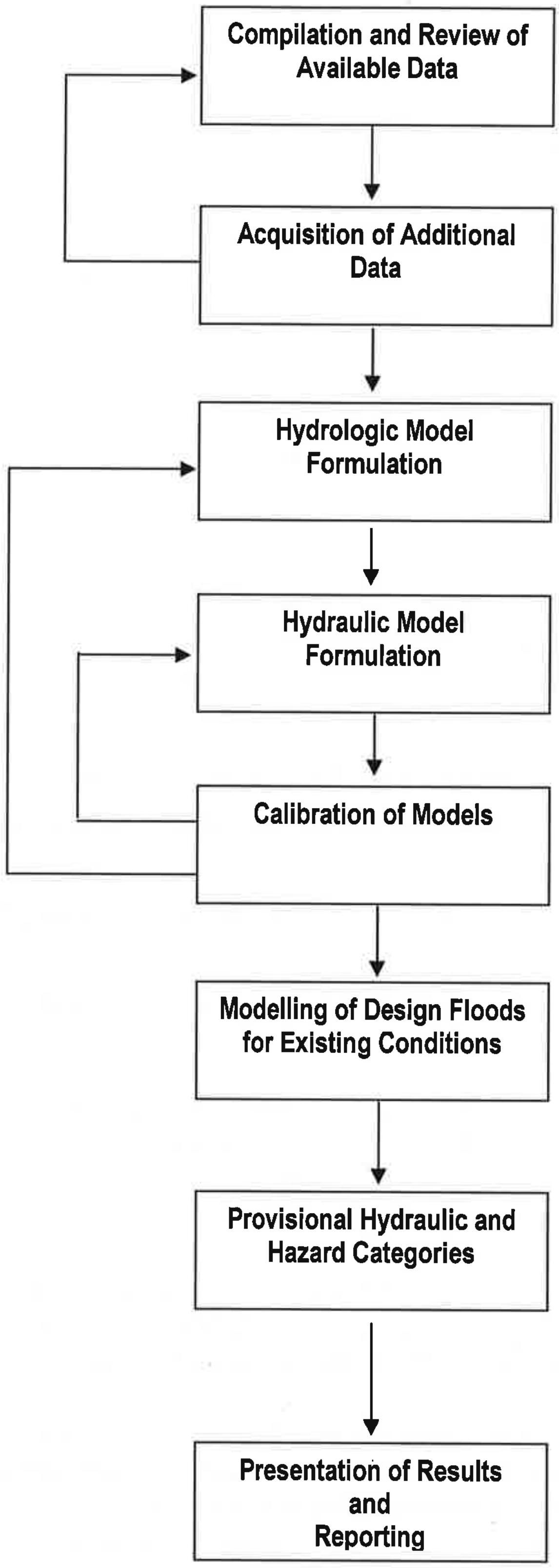
- the use of flood liable land is planned and managed in a manner compatible with the assessed frequency and severity of flooding;
- flood liable lands are managed having regard to social, economic and ecological costs and benefits, to individuals as well as to the community;
- floodplain management matters are dealt with having regard to community safety, health and welfare requirements;
- information on the nature of possible future flooding to the public;
- all reasonable measures are taken to alleviate the hazard and damage potential resulting from development on floodplains;
- there is no significant growth in hazard and damage potential resulting from new development on floodplains; and,
- appropriate and effective flood warning systems exist, and emergency services are available for 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 becomes a baseline document summarising flood related data that can be used to resolve floodplain management issues.

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, and to highlight those areas where the greatest flood damage is likely to occur.

In particular, the study aims to characterise flood behaviour in the Turallo Creek catchment as it affects the village area of Bungendore. This work includes an examination and analysis of the hydrologic characteristics of the catchments of each of the three creeks that drain to Bungendore (*viz., Turallo, Halfway and Millpost Creeks*) and a detailed hydraulic study of the village and its immediate environs.

The flow chart shown below outlines the key steps and the sequence of work undertaken.


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

3.2 DETAILED DESCRIPTION OF METHODOLOGY

3.2.1 Compilation and Review of Available Data

Initially Council was visited to discuss details of the flood study. Relevant information and data was collected including previous studies, contour mapping, hydraulic structure dimensions and aerial photography. A reconnaissance of the study area was also undertaken and included meetings with local long-standing residents.

The local and regional offices of the Department of Land & Water Conservation were also contacted to acquire data. However, neither office had additional data available. Flow gauge data was extracted from the DLWC *PINNEENA 5* archive. The Bureau of Meteorology provided catchment-wide rainfall records.

The collected data was then assessed in terms of suitability for the purposes of the flood study and gaps in the data-set were identified. The gaps in the data are discussed in further detail in **Section 4**.

3.2.2 Acquisition of Additional Data

The various sets of contour plans made available by Council cover a large area of the 2-d hydraulic model area. However, an appreciable tract of land had no detailed contour information. A topographic and hydrographic survey brief was prepared to detail the collection of spot elevations across the floodplain and channel cross-section details for the three creeks. The extent of survey was kept to a minimum with the use of aerial photography that defined prominent geomorphic features.

This survey work was completed by Council and proved sufficient to complete further contour lines and ultimately produce a Digital Terrain Model of the hydraulic model study area.

The Digital Terrain Model has been provided to Council and DLWC with a backdrop of aerial photography and background cadastral information.

3.2.3 Formulation of Hydrologic and Hydraulic Models

Hydrologic models were formulated of the three creek catchments utilising aerial photography, topographical data and published model parameters. *RAFTS-XP,* which is an industry standard hydrologic modelling package, was used to formulate these models and subsequently run to simulate design and historical event rainfall. **Section 6** provides further details of the hydrologic modelling component, including the adopted model parameters.

The development of the 2-d hydraulic model depended upon the production of a reliable Digital Terrain Model (*DTM*) of the hydraulic model study area. The bounds of the hydraulic model study area were as defined in Yarrowlumla Shire Council's *Technical Brief*. The model network was formulated with a variable grid geometry using the *RMA* suite of software. Element elevations were extracted from the *DTM* and element surface roughness values were adopted based on an examination of aerial photography. Refer to **Section 7** for additional detail on the model formulation.

3.2.4 Calibration of Models

Model calibration provides a means to adjust assumed model parameters so that the formulated model is fine-tuned and capable of replicating (*within acceptable margins*) the discharges and floodwater elevations measured from historical flooding events. Calibration allows greater confidence to be placed in the results of both hydrologic and hydraulic modelling.

Due to shortcomings in the available flow and rainfall data a full calibration and verification of the hydrologic models was not possible. However, the utility of the data available was maximised in order to produce an acceptable calibration of the models (*refer* **Section 6.2**).

The hydraulic model of Bungendore was run with both design and historical event hydrographs. The 1974 flood (*a significant flooding event*) was used as a cross-check, with the estimated flood levels agreeing sufficiently well with the measured flood marks for confidence to be placed in the formulated model. Results of this model run and subsequent design event runs were presented to the Bungendore Floodplain Management Committee (*whom as a group possess a significant body of understanding of flood behaviour in Bungendore*) and model output concurred well with their local knowledge of flooding in the village.

3.2.5 Modelling of Design Events for Existing Conditions

Design flow hydrographs were produced in *RAFTS* and run through the *RMA* model network for a set of design storms. Events corresponding to the 100, 50, 20 and 5 year Average Recurrence Interval (*ARI*) were simulated through the model along with the Probable Maximum Flood (*PMF*), which utilised the Probable Maximum Precipitation (*PMP*) estimated from the Bureau of Meteorology *Bulletin 53*.

The critical storm duration for each return period, at each of the hydrologic catchment outlets (*Turallo, Halfway and Millpost*), was determined by running a range of storm durations through the model. The storm duration that resulted in the largest peak discharge at the outlet for that event was deemed to be the critical duration.

Note that all digital result files from the RMA modelling have been provided to Council and DLWC. All event simulation output (including discharge, velocities, depth of flow, provisional hazards etc.) can be graphically reviewed with an easy-to-use package Patterson Britton have provided. This presentation of results demonstrates the dynamic development of a flood and the behaviour of floodwaters as they pass through the village. A backdrop of both background cadastral mapping and aerial photography is included. An animation of the 1% AEP flood event is also provided.

3.2.6 Provisional Hydraulic and Hazard Categories

A set of plans has been produced defining flood hazard through out Bungendore, in terms of depth and velocity of floodwaters. These plans along with a discussion are to be found in **Section 9**.

4 AVAILABLE DATA

4.1 PREVIOUS INVESTIGATIONS

A number of previous investigations have been undertaken to examine the nature and extent of flooding at Bungendore. These include two flood studies that are documented in the following reports:

- *'Bungendore Flood Mitigation Study'* (*1976*)
- *'Elmslea Estate Flood Study'* (*1992*)

However, neither study assessed the full range of floods that can occur or considered the extent of potentially flood liable land within the village boundaries. An underlying tenet of the recently updated *'Floodplain Management Manual'* (*2001*) is the need to consider all floods up to and including the probable maximum flood (*PMF*). Neither of the previous flood investigations for Bungendore considered the PMF.

Notwithstanding, both of these investigations provide useful information and flood related data. A brief synopsis of each is presented in the following sections.

4.1.1 Review of Previous Flood Studies

Bungendore Flood Mitigation Study (*1976*)

The *'Bungendore Flood Mitigation Study'* (*1976*) was prepared for Yarrowlumla Shire Council by the Unisearch Ltd, which is a commercial arm of the Water Research Laboratory of the University of NSW. The study was commissioned following inundation of properties in the village during flooding of Turallo Creek in July 1991. The purpose of the investigation was to identify methods to prevent inundation of the village in floods up to the 100 year recurrence event.

A series of "desk-top" backwater calculations and statistical methods were employed to analyse the system and formulate recommendations.

A number of flood mitigation proposals were examined, including:

- the construction of a low lying levee system enclosing the flood prone areas of the village from the effects of Turallo Creek and Halfway Creek;
- the augmentation of the waterway area of the Bungendore Road bridge over Millpost Creek;
- the augmentation of the waterway area of the Bungendore Road bridge over Halfway Creek;
- the clearing of trees from Turallo Creek; and,
- construction of a diversion channel between Halfway and Millpost Creeks.

This study concluded that Bungendore could be protected from inundation in events up to and including the 100 year recurrence flood by the construction of a levee along the southern banks of Turallo Creek.

Elmslea Estate Flood Study (*1992*)

This study was prepared by Boyden & Partners for JD Kilmartin Pty Ltd. JD Kilmartin Pty Ltd owned land extending north from Turallo Creek and had plans to develop the site for rural and medium density land-uses. The land is commonly referred to as Elmslea Estate and is located at Bungendore North. Once completed, Elmslea Estate will comprise approximately 400 residential lots, potentially doubling the size of the village.

The purpose of the study was to determine the extent of inundation across the land proposed for development, in the 100 year recurrence flood. The study was based on hydrologic modelling of the catchments of both Turallo and Halfway Creeks and hydraulic modelling of the "village reach" of Turallo Creek.

Each catchment was modelled using the RAFTS software package. These discharges were then used as boundary conditions within a HEC-2 hydraulic model extending along Turallo Creek. The investigation focussed on flooding within the proposed subdivision, but also established a range of flood related information relevant to the entire village, including:

- determination of the 100 year recurrence flood level within Turallo Creek;
- determination of peak water surface profiles along the "village reach" of Turallo Creek, for a range of design flood scenarios; and,
- suggestions for the realignment of Turallo Creek in order to alleviate future flooding.

The following conclusions were drawn:

(i) The Tarago Road bridge acts as a hydraulic control which becomes overtopped in floods larger than the 1 year recurrence event.

(ii) Flood levels along Turallo Creek upstream of the Tarago Road bridge are not dependent on flow from the Millpost Creek catchment.

(iii) Construction of a flood bypass between the Tarago Road bridge and the confluence of Millpost and Turallo Creeks would only marginally reduce the frequency of flooding in the village

It was predicted that such a floodway would only reduce flood levels by 300 mm between the confluence of the two streams and the Bungendore Road bridge.

(iv) Inundation of Bungendore from overtopping of Turallo Creek could be prevented by construction of the levee system proposed and investigated for the *'Bungendore Flood Mitigation Study'* (*1976*).

4.1.2 Other Drainage Investigations

Consulting Engineers, Lyall Macoun, undertook a drainage investigation to size replacement culverts for the Kings Highway crossing of Halfway Creek. The crossing is located south of the village near the intersection of the Kings Highway and trucking Yard Lane.

Unfortunately, a copy of the report supporting the investigation was unable to be obtained.

4.2 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 NSW Department of Land & Conservation (*DLWC*), along with other government agencies such the State Rail Authority (*SRA*) and the Roads and Traffic Authority (*RTA*).

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

4.2.1 Topographic Data

A range of data is available that defines the topography of the floodplain in the vicinity of Bungendore. This includes:

- 1:25,000 series topographic mapping developed by the Central Mapping Authority (*CMA*);
- oblique and vertical aerial photography of the catchments of Turallo, Halfway and Millpost Creeks; and,
- some contour mapping of the village area.

Topographic Mapping

Broadscale topographic mapping covering the catchments that drain to Bungendore is contained on the following 1:25,000 series CMA maps:

- Bungendore 8727-II-N
- Sutton 8727-I-S
- Hoskinstown 8727-II-S
- Bombay 8827-III-S
- Manar 8827-III-N

These maps provide cadastral information, planimetric features and contours of land surface elevation at 10 metre intervals. They were published in 1980 and developed from aerial photography flown in 1976.

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 set of aerial photographs was flown in 1997. Stereoscopic pairs are available for this run.

Contour Mapping

Council provided a large set of contour mapping and spot elevations from various sources covering the town centre and some outlying areas. The Bungendore Sewerage Plans 1976 form the major component of this data-set. This contour mapping was digitised for use in development of a digital terrain model of the land surface through the town area.

4.2.2 Hydrographic Data

Only limited hydrographic survey data was available. This included:

- cross-sections of the channel of Turallo Creek between the Goulburn-Bombala Railway crossing and the Tarago Road crossing; and,
- bridge and culvert design details.

Council also provided design details of all relevant culverts and bridges. Copies of drawings showing the details of bridge crossings are enclosed in **Appendix A**.

4.2.3 Hydrologic Data

Historical Rainfall Data

A number of rain gauges are located within the catchments of the three creeks that drain to Bungendore. These include daily synoptic rainfall recorders managed by the Bureau of Meteorology and daily read rain gauges situated on rural properties located within the catchment. The locations of these gauges are shown in **Figure 3** and relevant details are listed in **Table 1**.

Table 1 SUMMARY OF RAIN GAUGES WITHIN THE BUNGENDORE CATCHMENT

RAIN GAUGE NAME AND REFERENCE NUMBER	DURATION OF RECORDS
Bungendore Post Office (*070011*)	1890 to present
Bungendore Public School (*070294*)	1890 to 1916
"Douglas" (*070030*)	1885 to 1973
"Gidleigh" (*070035*)	1886 to present
Hoskingtown Radio Observatory (*070048*)	1926 to present
"Old Kowen" (*070234*)	1970 to 1976

Source: Bureau of Meteorology

A brief analysis of the available daily read rainfall records was undertaken to identify the major rainfall events that could have contributed to simultaneous flooding of Turallo, Halfway and Millpost Creeks. A study of monthly rainfall maxima was carried out in order to give a broad overview of rainfall patterns. It showed that major storms occurred in 1925, 1959 and 1976. Flooding events such as the 1974 event did not feature, though the daily rainfall records do show significant rainfall measurements.

Streamflow Records

Streamflow data was obtained from the Department of Land & Water Conservation by direct inquiry and from their stand-alone hydrologic database (*PINEENA 6.1*). Two streamflow gauges were identified as being within the study area. Details of these gauges are provided in **Table 2** and their locations are shown in **Figure 3**.

Table 2 STREAMFLOW GAUGES WITHIN THE BUNGENDORE CATCHMENT

STREAM GAUGE	DURATION OF RECORD	AVAILABLE DATA
Millpost Creek at Bungendore (*Reference ID 411001*)	1959 to present	Maximum monthly water level and discharge
Turallo Creek at Bungendore (*Reference ID 411002*)	1971 to 1980	Maximum monthly water levels and discharges

Source: DLWC PINEENA 6.1 database

4.2.4 Historical Flood Marks

As discussed above, the available rainfall records were used to identify the dates of major storms that have occurred in the vicinity of Bungendore. The dates of these storms can provide an indication of the likely times of the worst floods that have occurred.

However, the occurrence of a major storm does not necessarily translate to a major flood. The prevailing wetness of the catchment at the time of onset of the storm can be equally as important.

Furthermore, the distribution of rainfall across the catchment can influence the severity of the flood. At Bungendore for example, major flooding is likely to occur after rainfall has fallen in the catchments of each of the three tributaries. Whereas, rainfall in the Halfway Creek catchment alone, may not result in significant flooding of the village.

In order to establish the most severe floods, searches of Council records and previous investigations were undertaken to identify historical flood marks. Historical flood marks provide a record of the height that floods have reached and can be used to calibrate models developed to replicate those floods. Consultation with the community was also undertaken in attempt to identify flood marks that may not have been surveyed previously.

Data from Previous Studies

A number of previous flood studies completed for the Bungendore area placed considerable emphasis on collecting available historical data as well as anecdotal evidence of specific flood events. The majority of this information is compiled in the report prepared in 1992 by Boyden & Partners.

Figure 4.1 of the Boyden & Partners report provides a summary of available flood marks, including the date and elevation of the recorded flood level. Yarrowlumla Shire Council provided the data presented in this figure. As part of investigations for this flood study, the data provided by Council has been updated so that the levels of all recorded floodmarks are specified relative to Australian Height Datum. The updated data has been reproduced for this report and is presented in **Figure 4**.

The majority of the flood marks are based on debris lines left across the floodplain of Turallo Creek after floods in 1956, 1974 and 1988. The remainder has been determined from personal accounts of the height that floodwaters reached and from watermarks on structures.

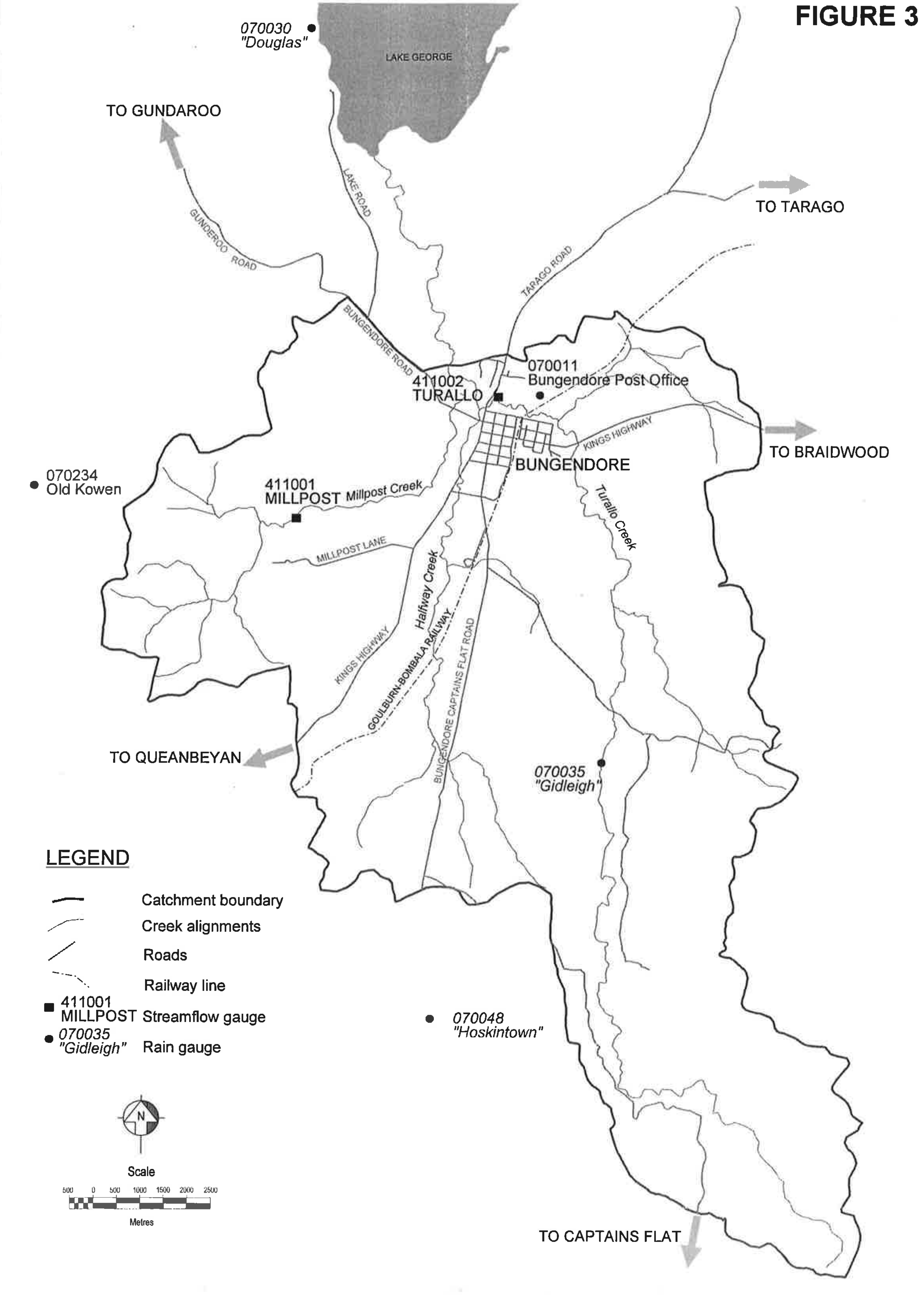
For example, watermarks on the railway "well shed" located near the Goulburn-Bombala Railway crossing of Turallo Creek, have been surveyed to determine historical flood levels at this location (*Boyden & Partners, 1992*) (*refer* **Figure 4**). A list of peak flood levels at this location is provided in **Table 3** for a range of major floods that have occurred at Bungendore.

Table 3 RECORDED PEAK FLOOD LEVELS AT RAILWAY WELL SHED

DATE OF FLOOD	PEAK RECORDED LEVEL (*mAHD*)
1909/1969	692.03
1904/1934	692.78
1950	692.13
1953	692.58
1956	691.78

A range of other historical flood marks and associated levels are shown in **Figure 4**. These are predominantly associated with the 1974 and 1988 floods. A comparison of recorded levels at two key locations within the village is provided in **Table 4**.

FIGURE 3



LOCATION OF STREAMFLOW AND RAIN GAUGES

FIGURE 4

LOCATION OF HISTORICAL FLOOD MARKS AT BUNGENDORE

Table 4 RECORDED FLOOD LEVELS AT BUNGENDORE FOR 1988 AND 1974 EVENTS

LOCATION	PEAK RECORDED LEVEL (*mAHD*)		
	1956 FLOOD	1974 FLOOD	1988 FLOOD
Upstream side of Tarago Road Bridge Crossing of Turallo Creek	-	690.55 (*North side*) 690.42 (*South side*)	690.14
Service station on NE corner of Gibralter and Molonglo Streets	690.88	690.37	689.43

Data from the Roads and Traffic Authority (RTA)

The RTA has measured a highest flood level under the Kings Highway bridge over Turallo Creek of 94.80 ft to an assumed datum. This level includes afflux through the bridge.

Consultation with Long Standing Town Residents

As a component of the data assessment phase for this study, interviews were held with two long-standing local residents identified by Council. These residents were:

- Mr Athel Gardener; and,
- Mr Stan Harrison.

Both Mr Gardiner and Mr Harrison have observed floods over many years and their recollections of specific events provide an insight into the pattern of floodwater movement through the village. Details of pertinent points from interviews with these residents are provided in the following.

Interview with Mr Gardener

Mr Gardener is a long-term resident and former proprietor of the Shell Service Station on the corner of Gibraltar Street and Tarago Road (*as shown on the front cover of this report*). He made the following points in relation to questions about historical floods in the village:

- 1951 is the largest flood in his memory, with up to 3 feet of water in areas of the town. At the peak of the 1951 event, floodwaters lapped the step at the entry to the *Old Wares* shop on Ellendon Street. Floodwaters entered the bar of the Lake George Hotel.
- Floodwaters remained high for about four hours, but did not increase despite further rainfall in the town over this period.
- In Mr Gardener's opinion, the construction of a dam on the *"Gidleigh"* property (*refer* **Figure 1**) has reduced the potential for flooding of the magnitude of the 1951 event.
- Flooding has occurred in Bungendore without any rain in the village. Mr Gardener recalled incidences of heavy rain in the upper catchments of Turallo and Halfway Creeks that led to flooding in the town, although he could not recall the date of this event.
- Mr. Gardener also noted that in the wet years when Turallo Creek was cleared no flooding affected the village.

Interview with Mr Harrison

Mr Harrison is also a long term resident of Bungendore. He farms land along Mecca Lane (*refer* **Figure 4**). In Mr Harrison's recollection, the 1956 flood was the largest event, with floodwaters upstream of the railway bridge reaching within "18 inches" of the tracks. He recalled that floodwaters extended up along Main Street as far as the supermarket.

Other comments made by Mr Harrison included:

- Generally flooding occurs along Turallo Creek or along Halfway Creek, but rarely do both streams overtop their banks simultaneously (*as was the case in 1956*).
- The 1987 flood was also quite significant, with floodwaters surrounding his house and inundating his paddock.
- Mr. Harrison estimated that it typically takes between 8 to 10 inches of rain before flooding of the town.
- In Mr. Harrison's opinion clearing the creek would reduce flooding in the town area.

4.3 ADDITIONAL TOPOGRAPHIC AND HYDROGRAPHIC SURVEY

Whilst the available contour mapping covered a considerable portion of the hydraulic model area the extent and detail available were not sufficient to produce a DTM of the area. Geomorphic features such as localised hills, troughs and channel flowpaths were initially identified during field reconnaissance. The extent of these features were defined with the use of the aerial photography in order to ensure that the survey brief was fully inclusive of all features that may influence flooding patterns. With this understanding of the area it was possible to minimise the extent and cost of the survey.

The survey data (*provided as a set of spot elevations*) was viewed in a CAD package with the existing contour lines and aerial photographs identifying the relevant geomorphic features as a backdrop. Using this backdrop as a guide contour lines were developed from the survey data. This methodology ensured that sufficient contours were drawn to cover the entire study area and also adequately define the relevant geomorphic features.

The composition of the existing contour plans and the survey contour plans resulted in the production of a DTM. This DTM provided a base on which to formulate the RMA model and includes all geomorphic features relevant to flood behaviour in the hydraulic model.

The additional survey work Council completed was carefully planned to ensure that the topography and hydrography of the entire hydraulic model area would be sufficiently defined. A draft version of the resulting DTM was interrogated by Council, and their comments and suggestions were incorporated in the production of the final version of the DTM. These rigorous efforts have ensured that the quality of the DTM of the study area is acceptable for the purposes of two dimensional hydraulic modelling.

5 DESCRIPTION OF FLOOD BEHAVIOUR

5.1 CONCEPTUAL MODEL OF FLOOD BEHAVIOUR

The climate of the region can be described as temperate. The average annual rainfall of approximately 627 mm (*taken from the longstanding Bungendore and Gidleigh gauges*) seems to be reasonably evenly distributed across the catchment, with the "wet" months typically from October through to January. The Great Dividing Range, which is located just east of the catchment, provides a break for easterly relief rainfall.

Figure 5 provides a graphic interpretation of the conceptual hydrologic model and shows the apportionment of the study area into sub-catchments. This delineation was based upon variations in land-use, slope and tributary inflows. The relative magnitude of flow along the catchment is also indicated.

Turallo Creek, the major system in the catchment rises in the mostly forested Turallo Range and drains the range. As the creek flows towards Bungendore the floodplain flattens and clears to pastureland. There are no major inflows to Turallo Creek upstream of Bungendore, with a large number of tributaries draining to the creek. There are few hydraulic structures along the creek and no major storage areas. Upstream of Bungendore, flooding is not significant and mostly contained within the well defined creek.

In comparison, the Halfway Creek sub-catchments are flatter and predominantly pastureland. At the transition from the steeper upstream areas, which drain some of the Turallo Range, to the flat meandering course of the creek there are swampy areas of land. As the creek approaches Bungendore the slope flattens considerably with further wider bands of flooding.

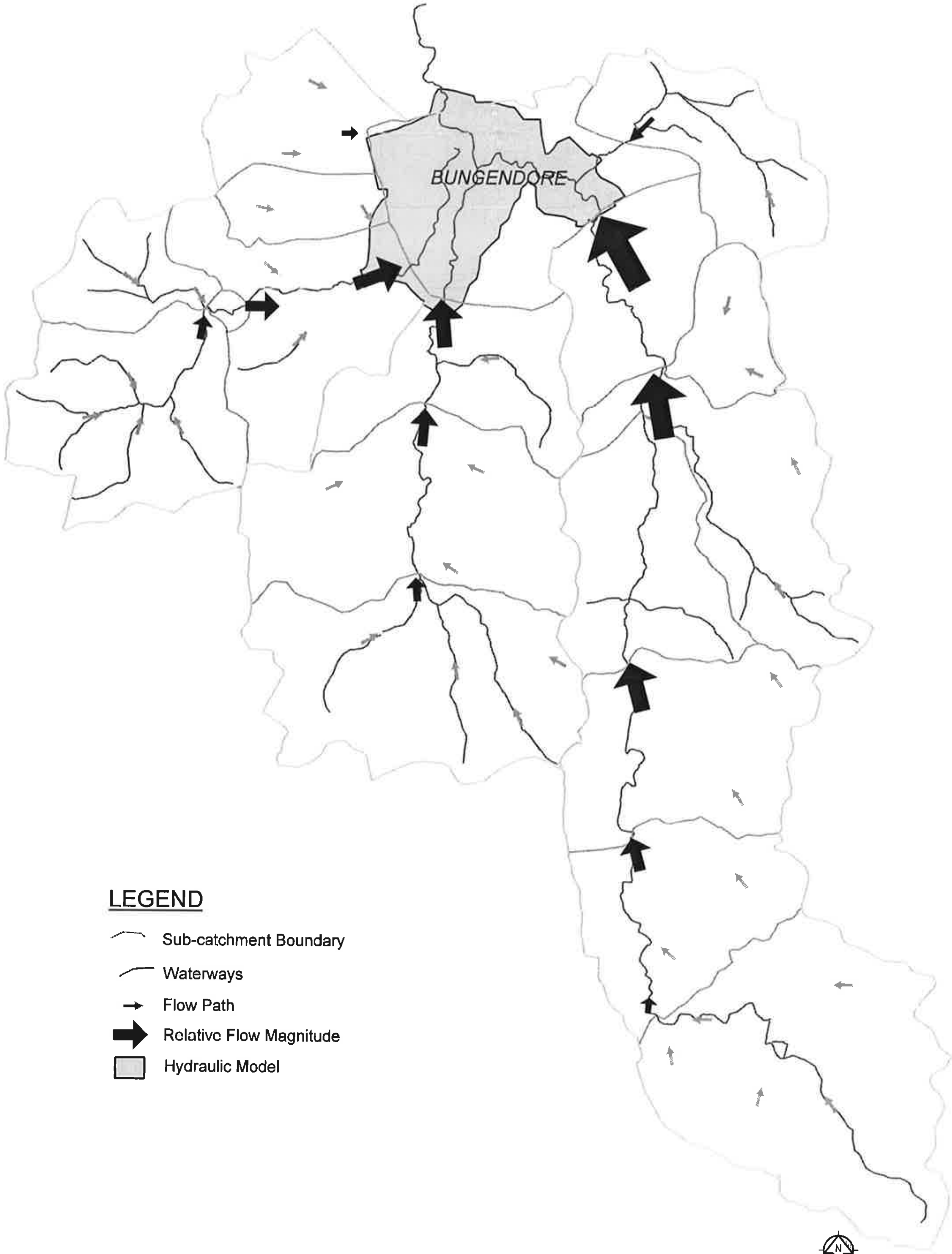
The upper reaches of Millpost Creek rise in the Lake George Range in a lightly forested area. As the creek makes it way towards Bungendore the slope flattens and the creek floods over a wide pasture floodplain, with a number of inflows to the creek are along poorly defined channels.

The conceptual model of hydraulic processes during significant flooding events has been produced in a schematic format in **Figure 6**. The model was developed following field observations, the examination of historical flooding records and the meetings with local residents familiar with flood behaviour in the village.

The figure identifies the major inflows to the system with their flow path and relative proportion of flow indicated. Significant overland flowpaths are also displayed with potential hydraulic control structures also identified.

The crucial delineation of individual elements for the *2-d* hydraulic model relied upon an understanding of the hydraulic processes as schematised in the conceptual model.

FIGURE 5



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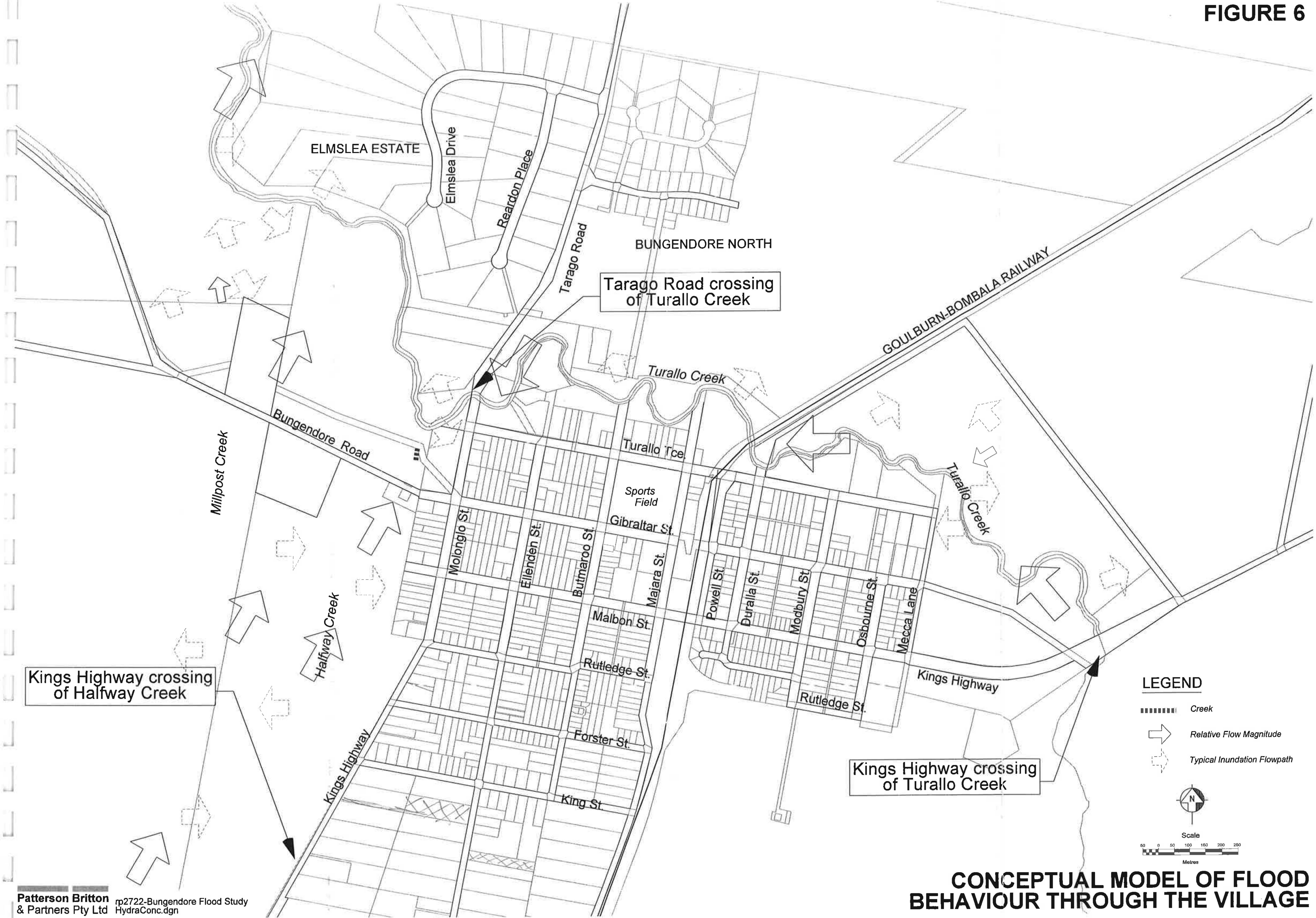
CONCEPTUAL MODEL OF
HYDROLOGIC PROCESSES

FIGURE 6



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CONCEPTUAL MODEL OF FLOOD BEHAVIOUR THROUGH THE VILLAGE

6 HYDROLOGIC MODELLING

6.1 MODEL DEVELOPMENT

The Runoff Analysis and Flow Training Simulation (*RAFTS-XP*) software package was employed to quantify flood discharges from the upper sections of the catchments of each of the three streams that drain to Bungendore. 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.

A RAFTS (*Runoff Analysis and Flow Training Simulation*) model comprises a network of nodes and links, with each node representing the point of discharge for a particular sub-catchment and each link representing the connecting channels. Sub-catchment data is assigned to a corresponding model node. A lag-time is assigned to each model link, with the hydrograph entering the top of the link translated by the lag to the bottom of the link.

Each of the three catchments was discretised into a number of sub-catchments (*refer* **Figure 7**). Each sub-catchment was defined so as to be relatively uniform in slope, soil type and land-use, typically with the outlet at a stream confluence and with all sub-catchments of the same order of size. This delineation was also designed so that the downstream sub-catchments (*refer* **Figure 8**) corresponded with the preferred locations of inflow hydrographs for the hydraulic model. Both aerial photography and topographical mapping were used to define the sub-catchment boundaries.

Design parameters (*both constant and variable*) were adopted on a sub-catchment basis, based upon site visits and investigations, aerial photography of the study area and published parameters for hydrologic modelling. Design storms for the catchments were formulated for both standard return period storms and the Probable Maximum Flood. The *Initial and Continuing Loss Model* method of estimating excess runoff in *RAFTS-XP* was used. The model requires an initial loss to simulate initial catchment wetting when no runoff is produced, followed by a constant continuing loss rate to account for infiltration once the catchment is saturated. Initial and continuing rainfall losses were estimated for each of the catchments. These estimations were based upon a calibration using established regional relationships and the limited rain and flow gauge data available.

Peak flow rates and runoff volumes for design storm simulations including the Probable Maximum Flood (*PMF*) were determined for the adjusted hydrologic models. Flow hydrographs were produced for input to the hydraulic model, at a number of locations, using design rainfall patterns. The Probabilistic Rational Method was used as a desk-top cross-check of the model predicted peak flows.

6.1.1 Available Data-sets

Three historical flooding events in Bungendore are particularly recalled by residents as significant: 1956, 1974 and the 1988. The most extensive set of floodmarks available relate to the August 1974 flood.

Two flow gauges have been operational in the recent past in the Turallo and Millpost catchments (*refer* **Section 4** *for further details).* The Turallo flow gauge recorded flows from 1971 to 1980, with considerable gaps in the data including the 1974 flood. However, as this gauge is located on the largest creek in the system events recorded at this gauge may best represent the flooding characteristics of the village. The October 1976 flood was the largest recorded event at the Turallo Creek gauge. Records for the Millpost gauge extend from 1959 to the present. The 1974 flood was registered at the gauge and the next largest recorded event was the 1976 flood.

Several rain gauges are located throughout the catchment with extensive records (*refer* **Section 4**). The *Old Kowen* gauge has been nominated to be the representative gauge for the Millpost and Halfway catchments. The gauge at *Gidleigh* records rainfall to the Turallo catchment. Rainfall records confirm that both the August 1974 and October 1976 rainfall events were significant.

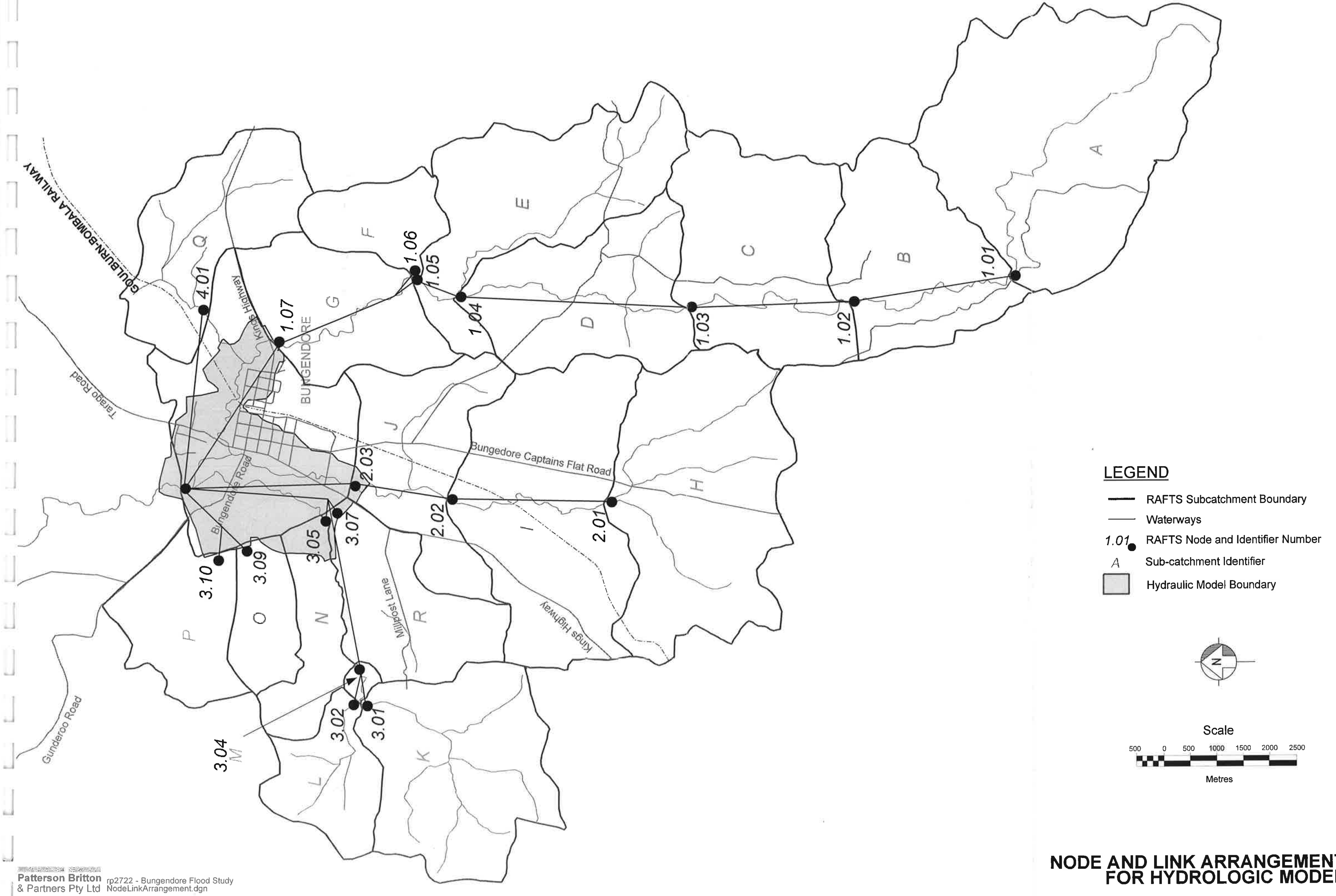
An examination of the records of all rain-gauges within the study area for both the 1974 and 1976 events highlighted a disparity in the measured rainfall at the *Gidleigh* gauge for the 1976 event. An approximately linear relationship was evident between the 1974 and 1976 rainfall measurements for all other catchment gauges other than *Gidleigh.* This discrepancy in rainfall measurement does not lend itself to input to a uniform rainfall distribution model and as a result the *Gidleigh* rainfall measurement was replaced by the *Old Kowen* rainfall for the 1976 event in the model runs.

The August 1974 flood was nominated as the most suitable historical event to calibrate the model, based upon the quantity of flood and debris marks and the available rainfall and flow data. However, due to the critical gap in the August 1974 data at the Turallo flow gauge the October 1976 flood was nominated as a base flood, by which to compare with the 1974 flood. For further details of the calibration of the hydrologic model refer to **Section 6.2.**

6.1.2 Regional Relationships

Due to a shortfall in the available data, a full calibration of the hydrologic model was not possible - calibration would have required regularly recorded (*eg. on an hourly basis*) rainfall and flow gauge data from recognised historical flood events. Calibration would have involved the input of rainfall records to the RAFTS model, with flow hydrographs produced as output at the location of each of the flow gauges. The flow hydrographs produced by the mathematical model would then have been compared with the measured flow hydrographs for features such as peak flow, cumulative volume and hydrograph lag-time. In order to match the set of hydrographs at each gauge, adjustment would have been made to the formulated model for assumptions such as rainfall losses, link lag-times and sub-catchment surface roughness.

FIGURE 7



NODE AND LINK ARRANGEMENT FOR HYDROLOGIC MODEL

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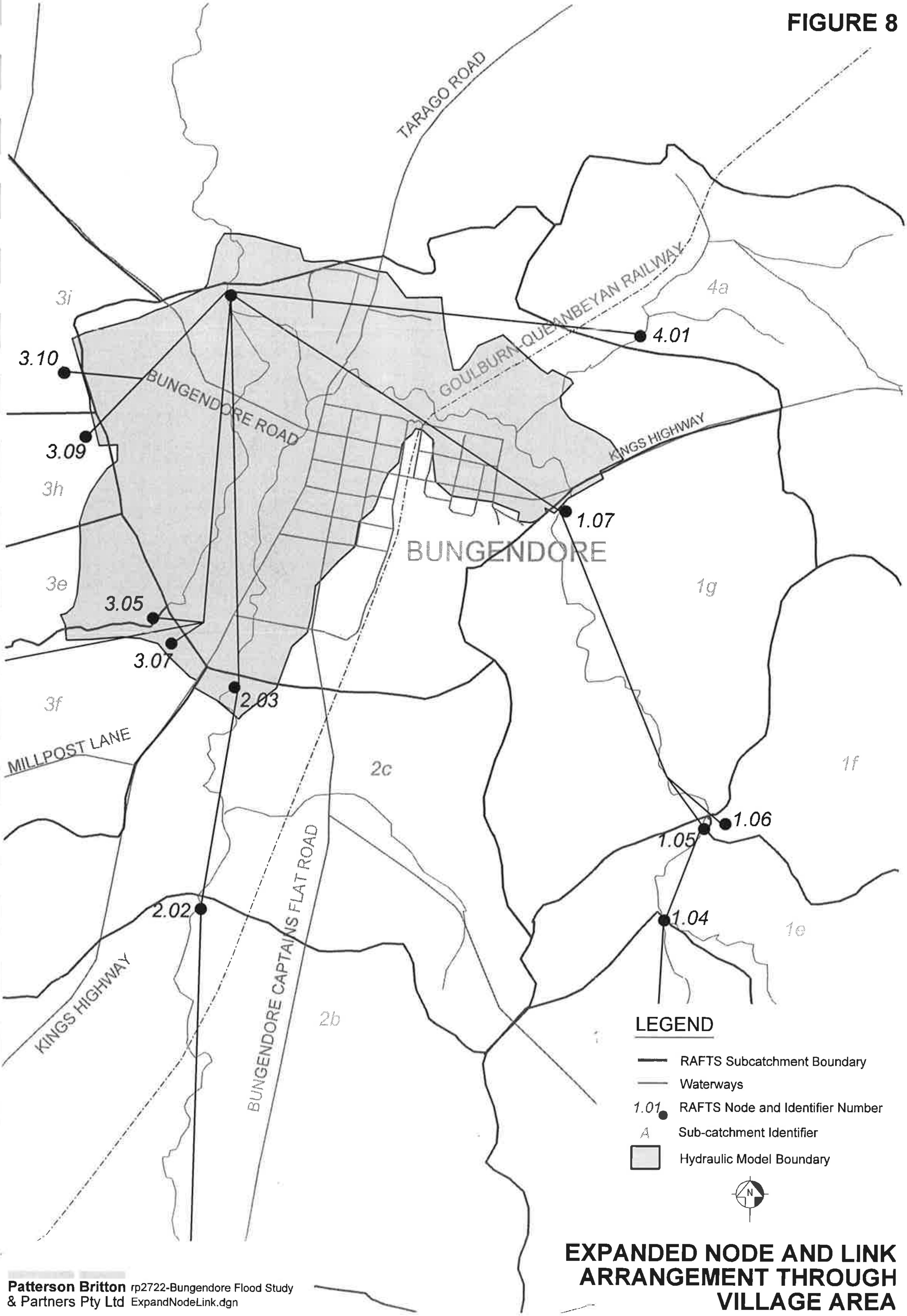
FIGURE 8



LEGEND

- RAFTS Subcatchment Boundary
- Waterways
- 1.01 RAFTS Node and Identifier Number
- A Sub-catchment Identifier
- Hydraulic Model Boundary

EXPANDED NODE AND LINK ARRANGEMENT THROUGH VILLAGE AREA

In the absence of suitable flood and rainfall data to complete a full calibration model parameter values must be estimated. *Australian Rainfall & Runoff (1987)* suggests a number of methods:

- *Adjacent catchments*
  This method involves comparing the study area with preferably two or three adjacent catchments with similar characteristics. This would require nearby gauged catchments whose flood characteristics are similar to those of the study catchment. Hydrologic models of these adjacent catchment models would need to be formulated and calibrated. Relationships would then be developed between the study catchment area and a particular catchment. This relationship would be applied to the model parameters.

  The NSW Department of Land & Water Conservation surface water data archive *PINNEENA 5* and Bureau of Meteorology records were examined in an effort to identify the existence of pluviographic data for other applicable catchments within the region. This search was not fruitful.

- *Estimation based on physical considerations*
  This method is typically employed where a previously calibrated model of the catchment exists and where changes to land use or conditions on the catchment have occurred. No such data is available for Bungendore and thus this method is not applicable to this study.

- *Regional relationships*
  Relationships for model parameters have been derived for several broad regions and are quoted in *Australian Rainfall & Runoff*. Caution is generally required when using these relationships as they are based upon the analysis of several catchments within the region that are not necessarily similar in nature and/or response to the catchment under investigation. For the purposes of this study a refinement of this methodology was adopted which reflected the individual characteristics of the Bungendore catchments, rather than adopt a set of published parameters without some interrogation.

6.1.3 Model Assumptions

The RAFTS software structure requires that a set of parameters (*both measured and assumed*) be defined for every sub-catchment, namely:

- *sub-catchment area* – defined as impervious and pervious areas, measured using both cadastral and aerial photography information;
- *physical characteristics of each sub-catchment*- slope, drainage paths etc. measured from available contour and topographical information;
- *PERN Value ('n') (also known as Mannings 'n' value)* - surface roughness factor, based on land-use, utilising aerial photography and on-site inspections;
- *initial rainfall loss* – assumed rainfall loss where no runoff occurs until the initial loss capacity is satisfied, values assumed with reference to *Australian Rainfall & Runoff*, and
- *continuing rainfall loss* – assumed constant loss throughout the rainfall event, values assumed with reference to *Australian Rainfall & Runoff*.

Impervious and Pervious Areas

The RAFTS model structure is such that for each sub-catchment pervious and impervious areas are defined as a percentage of urbanisation. For the rural conditions within the catchments, an impervious area as a percentage of the total measured area was assumed to be 5% for all of the sub-catchments. The RAFTS-XP Manual (*WP Software, 1992*) suggests the use of 0% impervious areas for rural sub-catchments. The 5% impervious area chosen accounted for impervious surfaces such as roads and roofs. Common practice suggests that the use of the 5% impervious area is reasonable.

Adopted Roughness Values (PERN)

Surface roughness values were adopted, based on the *RAFTS* manual recommended values. These are provided in **Table 5**.

Table 5 ADOPTED ROUGHNESS VALUES

CATCHMENT SURFACE	ROUGHNESS VALUE
Impervious	0.015
Urban Pervious Area	0.025
Rural Pastures	0.050 – 0.070
Forested Catchments	0.100

Source: RAFTS Manual, Version 2.80 (WP Software, 1992)

Adopted Rainfall Losses

Rainfall losses, as parameters in hydrologic modelling, help estimate the relation of runoff to rainfall and are specific to land-use.

Design loss rates based on regional relationships are published in *Australian Rainfall & Runoff* (*I. E. Aust, 1987*). Quoted loss rates for New South Wales are only appropriate to those catchments east of the Dividing Range or with an arid climate, neither of which satisfactorily describe any of the three catchments. However, other more applicable rainfall loss-sets are also quoted in **Table 6**.

Table 6 RECOMMENDED RAINFALL LOSSES

CATCHMENT	INITIAL LOSS (mm)	CONTINUING LOSS (mm/hr)
Molonglo River	-	1.9
Rural Catchments, ACT (*based on the calibration and regression analysis of three catchments*)	0	*2 Yr ARI* 3.6 *3 Yr ARI* 3.3 *10 Yr ARI* 2.8 *20 Yr ARI* 1.7 *50 Yr ARI* 1.0

Source: Australian Rainfall & Runoff (I. E. Aust, 1987)

As the Molonglo River catchment is immediately adjacent to the three catchments of Turallo, Halfway and Millpost it would seem reasonable to assume that the Molonglo catchment rainfall losses would be indicative of the losses within the bounds of the study area. However, these losses were not immediately adopted. Rather these loss values were the initial values set (*of each of the three models*) in an iterative series of model runs that maximised the value from the limited recorded data-sets available. This iterative procedure formed the basis of the *calibration* of the hydrologic model.

6.2 MODEL CALIBRATION

As only the 1974 flooding event resulted in a reasonable quantity of flood marks, flow and rainfall records, this event was chosen to calibrate the hydrologic model and verify the hydraulic model. Council was consulted on preliminary calibrated modelling results and their comments were considered in subsequent calibration of the model.

As mentioned previously, the August 1974 and October 1976 flooding events were both selected to calibrate the hydrologic model. Unfortunately, there are significant discontinuities in the Turallo data-set, perhaps due to gauge malfunctions. The most critical omission being data from the 1974 flood. The 1974 flood is of particular interest for a number of reasons, including the fact that it was a relatively large event that occurred in the recent past with records of the event such as photographs and floodmarks readily available. This type of additional data provides a guide to flood behaviour and also allows cross-checks of the hydraulic modelling result. However, the Millpost Creek flow gauge remained operational during the 1974 event.

In order to maximise the available flow data both sets of measurements were examined to ascertain if any relationship could be interpolated. The October 1976 event was found to be of the same order of magnitude as the 1974, with measurements at both gauges available.

When comparing the Millpost gauge hydrographs for the two events it was determined that the response of the gauged catchment to rainfall was quite similar, following comparative antecedent conditions. For this reason it was deemed reasonable to develop relationships between the 1974 and 1976 events at this gauge. Ultimately, these relationships were used to produce a 1974 hydrograph utilising the measured 1976 Turallo hydrograph.

Further details of the streamflow records are included in, **Appendix B**.

As previously mentioned, the 1974 event has been nominated as the calibration event for this study. An iterative procedure was developed to identify the most appropriate rainfall losses for each of the three sub-catchments, utilising the available catchment data of both the 1974 and 1976 events. As identified previously, the flow-gauge records for the 1976 event are more complete than the records from the 1974 event and hence, it was necessary to carry out this calibration process for both events at both gauges.

The calibration process involved inputting to the model the recorded daily rainfall for a recognised historical flooding event. A suitable temporal pattern was adopted for the models and a set of assumed initial and continuing rainfall losses were input (*using the Molonglo catchment rainfall losses as a reasonable starting point*). Output hydrographs were created from the model run at nodes corresponding to the flow gauge locations. Cumulative volume and peak flow were extracted from the hydrographs and each model was run a number of times with different sets of rainfall losses. The set of initial and continuing losses that produced both the volume and flow in the model hydrograph that corresponded best to the volume and flow of the historical event were adopted as the rainfall loss set.

Setting the goal hydrograph cumulative volume and flow was not quite straightforward. Flow has been measured at the Millpost and the Turallo flow gauges as a cumulative daily flow. Both cumulative volume and peak flow, as produced in a hydrograph, define a catchment's characteristic. With no measured peak flow data a further avenue of investigation had to be pursued. This work involved both flood frequency analysis and the use of the Probabilistic Rational Method.

Initially flood frequency analysis was completed on data from the Millpost gauge (*the period of record for the Turallo gauge was insufficient for flood frequency analysis*). A partial series flood frequency analysis estimated the annual return interval of the 1976 flood to be approximately 20 years (*refer* **Appendix B**). The Probabilistic Rational Method then estimated a peak flow for an Average Recurrence Interval (*ARI*) of 20 years for the Millpost gauge catchment. The measured cumulative volume and the estimated peak flow were then adopted for the October 1976 flood. Adjustments were made to the initial and continuing rainfall losses in the model, until the model hydrograph and the goal hydrograph were matched within a reasonable tolerance.

The result of this work was a set of rainfall losses for the Millpost Creek catchment for the 1974 calibration event. This procedure was then repeated at the Turallo Creek gauge for the 1976 event and at the Millpost gauge for the 1974 event. A relationship was also defined between the adopted rainfall losses at the Turallo gauge and the Millpost gauge for the 1976 event. This relationship was of use in selecting a suitable set of rainfall losses at the Turallo gauge for the calibration event.

As the Halfway Creek sub-catchment is similar in nature to the Millpost sub-catchment it has been assumed that the losses estimated for the Millpost catchment also applicable to the Halfway Creek sub-catchment. The adopted rainfall losses for the three sub-catchments have been applied to all design and historical event runs of each of the Bungendore models (*refer* **Table 7**).

Appendix C summarises assumed model parameters, on a sub-catchment basis.

Table 7 ADOPTED RAINFALL LOSSES

CATCHMENT	ADOPTED INITIAL RAINFALL LOSS (mm)	ADOPTED CONTINUING RAINFALL LOSS (mm/hr)
Halfway	0	1.7
Millpost	0	1.7
Turallo	0	1.9

6.3 SENSITIVITY ANALYSIS

A sensitivity analysis of model assumptions was completed to assess the effect of these assumptions on model output. The discharge point of Turallo Creek to the hydraulic model (*Node 1.07*) was chosen for this analysis as the creek plays a significant role in the flooding characteristics of Bungendore with 48% of the study area discharging to this point. Two critical assumptions were tested:

- *Assumed PERN (or surface roughness) values and,*
- *Antecedent and persistent rainfall conditions.*

6.3.1 Surface Roughness

Adopted surface roughness values were based upon published values, as discussed previously. In this sensitivity analysis the Turallo model was run with two alternative sets of surface roughness values, in order to assess the relative effect of this assumed parameter on the model output, quantified as peak discharge. The alternative roughness sets were +/- 20% of the adopted values.

Only significant changes in land-use practices would result in change in surface roughness of this magnitude. However, the results of the sensitivity analysis in **Table 8** demonstrate that these unlikely changes in land-use do not have a major impact on estimated peak discharges.

Table 8 SURFACE ROUGHNESS SENSITIVITY TURALLO CATCHMENT, 100 YEAR ARI

DESCRIPTION	PEAK DISCHARGE (m^3/sec)
Set of surface roughness values, as adopted	261
+20% adopted roughness values	243
-20% adopted roughness values	284

6.3.2 Rainfall Conditions

The sensitivity of the predicted model discharges to rainfall conditions can be tested by an adjustment of the assumed initial and continuing rainfall losses. The calibration of the hydrologic model for the Turallo Creek catchment suggested an initial loss of 0mm and a continuing loss of 1.9 mm/hr.

The model was run with two alternative published rainfall loss sets for the 100 year ARI design storm. The details of these loss sets and the results of the model runs are tabulated in **Table 9**.

Table 9 RAINFALL LOSS SENSITIVITY TURALLO CATCHMENT

DESCRIPTION	INITIAL LOSS *(mm)*	CONTINUING LOSS *(mm/hr)*	PEAK FLOW *(m³/sec)*
Losses as adopted for the Bungendore Flood Study	0	1.9	261
Losses for Rural Catchments, ACT, 100 year ARI *Ref. Australian Rainfall & Runoff, 1987*	0	1.0	276
Typical losses for New South Wales, east of the Dividing Range *Ref. Australian Rainfall & Runoff, 1987*	20	2.5	100

These results show that the peak flow calculated by the formulated model is sensitive to the adopted rainfall losses. However, comparing the peak discharge estimated using losses for rural catchments in ACT with that estimated using the adopted losses shows the difference in continuing losses does not have a notable impact on the resulting discharge. The effect of the adopted initial loss appears to be more significant to the resultant peak flow than the adopted continuing loss.

The rainfall losses, for catchments to the east of the Dividing Range, as recommended in *Australian Rainfall & Runoff* (*refer* **Table 9**), were based upon the analysis of a number of catchments in that region, which are characteristically forested and quite dissimilar to the study area. The significant difference in resultant peak flow as calculated, using the adopted losses and those *AR&R* recommended losses highlights the dissimilar nature of the catchments.

The adoption of suitable hydrologic parameters is significant in the prediction of discharge to the hydraulic model. A central goal of a flood study is to produce a quantification of flood behaviour throughout the study area, including flow depths and velocities, which are predicted from the hydraulic modelling component. In that regard the significance of the assumed hydrologic parameters is not as notable as those assumptions made for the construction of the hydraulic model. For instance, the assumed tailwater levels for the hydraulic model simulations, exert a much more notable effect on modelling results than parameters such as surface roughness or rainfall loss.

7 HYDRODYNAMIC MODEL

7.1 CATCHMENT DESCRIPTION

The study area for the hydraulic modelling component of the study focussed on the floodplain within the village zone. Council defined the area as bounded to the south along a line 500m south of and parallel to Trucking Yard Lane, to the east at the crossing of Turallo Creek by the Kings Highway and a point 300m downstream of the Turallo Creek / Millpost Creek junction. This study area is defined in **Figure 9**.

7.2 MODEL FORMULATION

The *RMA-2* software was used to develop a two dimensional hydraulic model of the village area. *RMA-2* is a fully two dimensional finite element model developed by Resource Management Associates, USA and Prof. Ian King, University of California at Davis. It uses finite element methods to solve 2-d depth averaged equations for turbulent energy losses, friction losses, and horizontal momentum transfer, and offers significant benefits over the more traditional finite difference techniques.

The primary benefit is the use of a variable grid geometry employing elements with irregular and curved boundaries that can be modified as required without the need for regeneration of the entire grid. This capability allows any shaped boundary to be modelled exactly. *RMA-2* has also been developed with the unique feature that permits the simulation of systems that flood and dry during the analysis period (*refer to* **Appendix D** *for further details on the RMA-2 software*).

The *RMA-2* model network (*refer* **Figure 10**) was developed utilising aerial photography, cadastral, contour and mapped geomorphic features as a background. This network extended over the defined floodplain, with elements and nodes defining the bed/surface elevation and roughness.

The contour information provided was combined with the hydrographic and topographic survey data collected to produce a digital contour plan. This contour plan was refined to include geomorphic features influential to flooding patterns, which were identified and defined during field investigations and from aerial photography. The considerable effort exerted to generate this contour plan resulted in a quality and reliable digital terrain model (*DTM*) of the study area. The DTM was defined on a three metre grid. With the aerial photography and DTM as a background the graphical delineation of the individual network elements readily took into account the topography and relevant features of the study area. Each element is defined by corner nodes and mid-side nodes and each of these node adopts its elevation from the DTM.

A surface roughness value was assigned to each defined element. The backdrop aerial photography was utilised in conjunction with detailed terrestrial photography (*from field investigations*) to assign a surface roughness value (*Manning's 'n'*) to each element individually. It should be noted that where velocities are not high (< 0.5 m/s) the effect of changes in roughness values are rarely significant to peak water levels. Flooding behaviour in Bungendore is typically over a large width and not necessary confined to defined channels.

Therefore, the results of hydraulic modelling will be more sensitive to the floodplain geometry than assumed surface roughness values.

A set of five surface conditions were used to define the study area (*refer* **Table 10**).

Table 10 ASSIGNED SURFACE ROUGHNESS VALUES

Description of Surface	Manning's 'n'
Defined channel	0.045
Pasture, no brush, high grass	0.038
Cultivated areas / Short grass	0.030
Scattered brush, heavy weeds	0.055
Village centre and scattered housing	0.04

Source: HEC-RAS Hydraulic Reference Manual

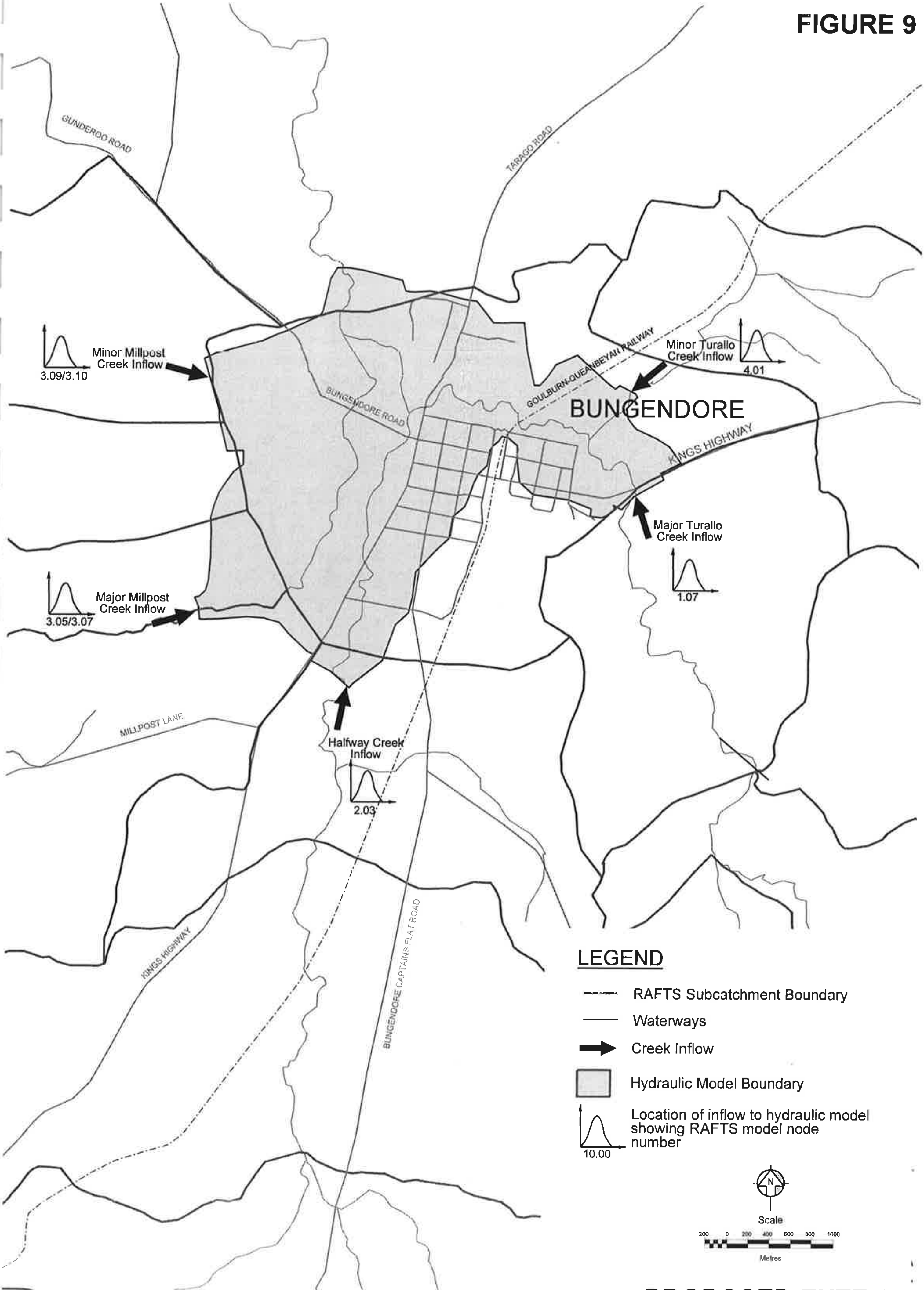
7.3 MODEL VERIFICATION

A check on the overall veracity of the formulated hydraulic model was achieved by comparison with historical flood marks and debris lines (*refer* **Figure 4**). Flood marks from the 1956 (*approximately the 100 year ARI event*) and the 1974 event (*the nominated calibration event*) were compared with the model output. Adjustments to the model including surface roughness values, tailwater levels and network generation were made accordingly.

The adoption of tailwater levels were based on an iterative process. Initially the level was estimated using normal depth calculation at the outlet of the model. The tailwater level was then calibrated using the available historical floodmarks and debris levels for the 1974 event and the 1956 event (*100 year ARI event*). With a reasonable coincidence with the historical marks, the 1974 and 100 year ARI tailwater levels were adopted. The tailwater levels for the remaining events were adopted by first estimating the level using normal depth calculations and then altering the level by a similar scaled amount to the two calibrated tailwater levels.

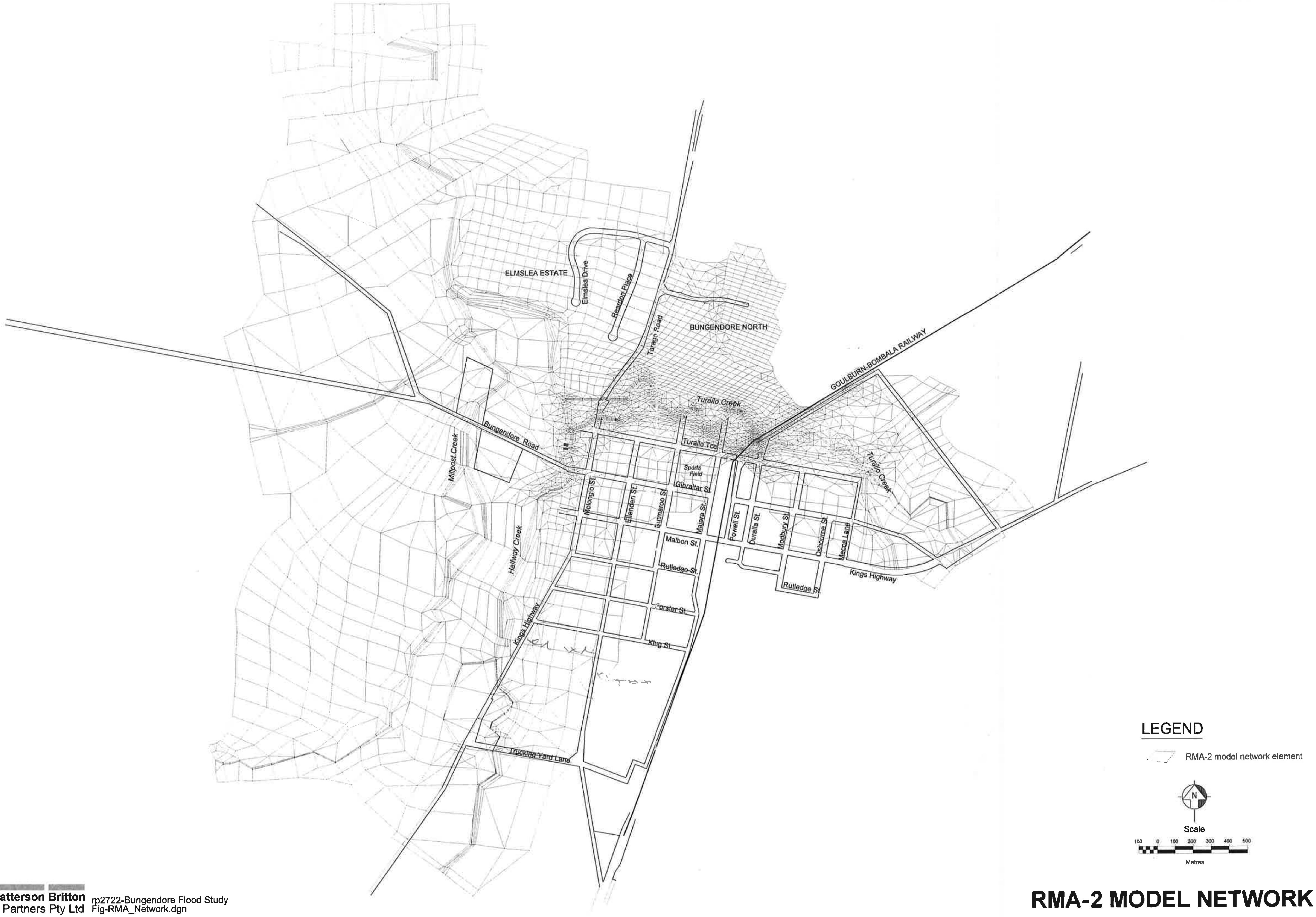
The modelled contours of the peak water surface for the 1974 event are shown in **Figure 11**. The predicted water surface profiles along Halfway Creek and Turallo Creek taken from this surface (*refer* **Figures 12 and 13** *respectively*) compare well with the limited available historical data. The predicted water surface for 100 year ARI event at the Gibraltar Road Service Station coincided exactly with the 1956 floodmark. Taking onto account both the inaccuracies involved in identifying the actual peak water mark and the tolerances of prediction possible from a formulated model of such extent, it is considered that the formulated *2-d* model predicts with a reasonable precision the flood behaviour within the study area.

FIGURE 9



PROPOSED EXTENT OF HYDRAULIC MODEL

FIGURE 10



Patterson Britton & Partners Pty Ltd rp2722-Bungendore Flood Study Fig-RMA_Network.dgn

RMA-2 MODEL NETWORK

FIGURE 11

CONTOURS OF PEAK WATER SURFACE FOR THE 1974 FLOOD

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J 2722 / R 1913
FIGURE-74event.DGN

FIGURE 12

MODELLED WATER SURFACE PROFILE
ALONG HALFWAY CREEK FOR THE 1974 FLOOD

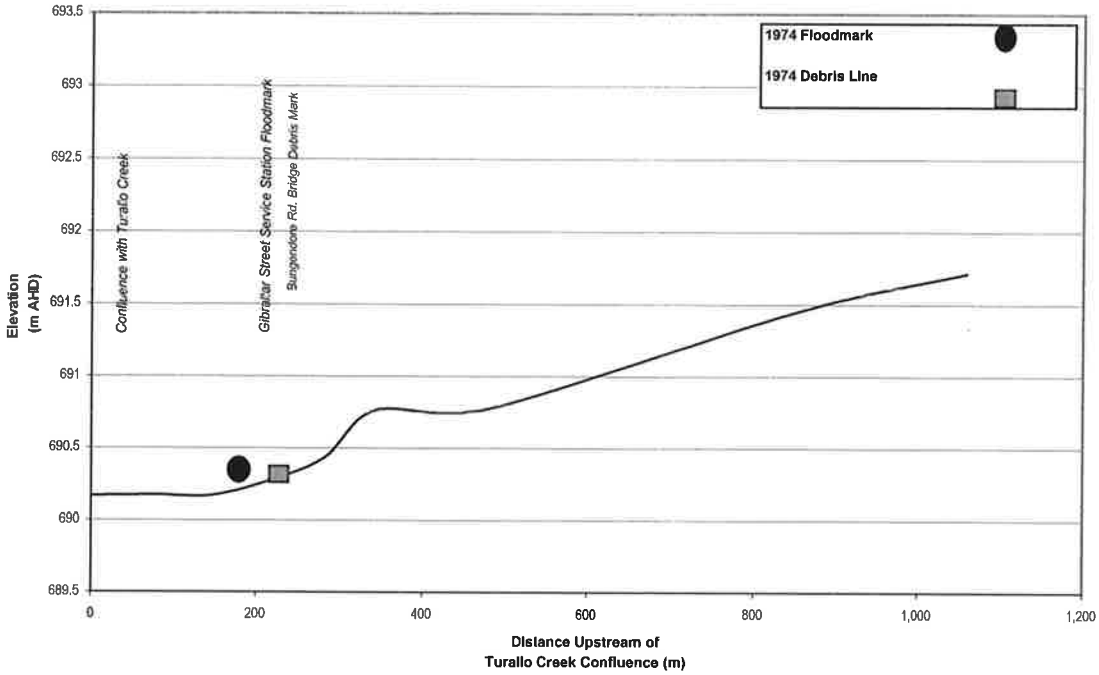
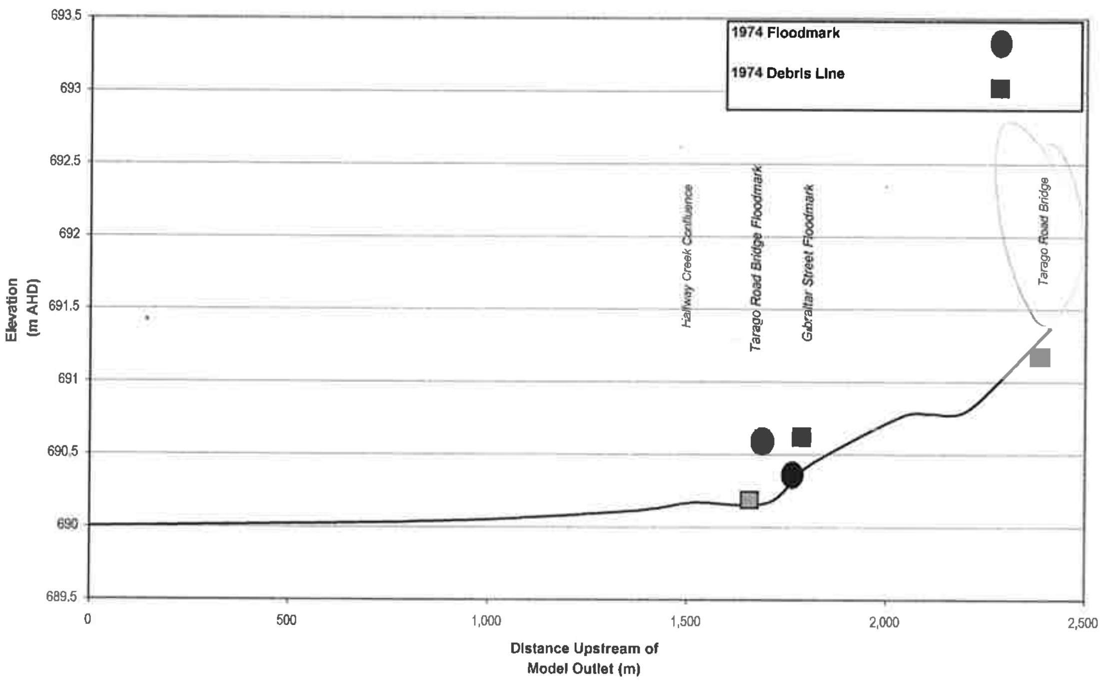


FIGURE 13

MODELLED WATER SURFACE PROFILE
ALONG TURALLO CREEK FOR THE 1974 FLOOD



8 DESIGN FLOOD ESTIMATION

8.1 HYDROLOGY

8.1.1 Design Storm Simulations

Design Rainfall Data

The RAFTS model described in **Section 6**, 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 Bungendore were developed using these procedures and are enclosed in **Appendix E**. A summary of rainfall intensities for major storm frequencies is provided in **Table 11**.

Table 11 DESIGN RAINFALL INTENSITIES FOR BUNGENDORE

STORM DURATION (*hours*)	RAINFALL INTENSITY (*mm/hr*)			
	5 Year ARI	20 Year ARI	50 Year ARI	100 Year ARI
0.5	44.2	58.4	69.4	78.0
1.5	22.5	29.2	34.3	38.4
2.0	18.5	24.0	28.2	31.5
3.0	14.0	18.1	21.3	23.8
6.0	8.8	11.2	13.2	14.7
9.0	6.7	8.6	10.0	11.1
12.0	5.4	7.0	8.1	9.1

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

Critical Storm Duration

A range of storm durations were considered and modelled to establish the critical storm duration for the catchment draining to Bungendore. A summary of the results of simulations undertaken to determine the critical storm duration is presented in **Table 12.**

The critical storm duration was assumed to correspond to the maximum peak discharge at Bungendore as generated using the RAFTS model. A critical storm duration of 6 hours was determined for the Turallo Creek catchment.

Table 12 CRITICAL DESIGN STORM DURATION

CATCHMENT	RAFTS MODEL NODE	CRITICAL STORM DURATION (*hours*)			
		5 Year ARI	20 Year ARI	50 Year ARI	100 Year ARI
Turallo Creek	1.07	6	6	6	6
Turallo Creek	4.01	6	6	6	6
Halfway Creek	2.03	6	6	6	6
Millpost Creek	3.10	3	3	2	2
Millpost Creek	3.11	3	3	2	2

In the instance where all three creek systems are responding to a rainfall event it can be assumed that the Turallo Creek critical durations apply as this creek is the major contributor to the catchment.

Peak discharges and flood hydrographs were generated throughout the catchment for a range of flood frequencies using the critical storm duration of 6 hours and the corresponding rainfall intensities and design temporal patterns. In accordance with the study brief, these flood frequencies included the 100, 50, 20 and 5 year ARI events, as well as the Probable Maximum Flood (*PMF*).

8.1.2 Probable Maximum Flood

The probable maximum flood (*PMF*) is the largest flood that could conceivably occur at a particular location. It is often referred to as a "flood of biblical proportion". Although floods of this magnitude are extreme, they provide important criteria for consideration in the management of the residual flood hazard. 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.

In recognition of these factors, investigations were undertaken to assess the magnitude of the PMF and its potential impact on the village of Bungendore.

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.

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 Turallo, Halfway and Millpost Creeks catchments to derive the PMP for Bungendore.

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 Brookong Creek catchment. For this duration, the Probable Maximum Precipitation is estimated to be 360 mm. That is, for a PMF event to occur at Lockhart, it is estimated that 360 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 69 mm (*refer* **Appendix E**).

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.

The peak discharge for the PMF in the Turallo Creek catchment was determined by applying the temporally distributed PMP in the RAFTS hydrologic model. As the catchment area is only 150 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 100 year ARI design storm; that is, the rainfall losses presented in **Appendix C** were adopted in the modelling.

PMP calculations are based upon methods set down in *Bulletin 53-Amended, 1996* (*Bureau of Meteorology*). This methodology provides short duration (up to 6 hours) PMP rainfall intensities with a spatial distribution throughout each of the catchments (*refer to* **Appendix C** *for further details*). The Bureau of Meteorology methodology also provides a design temporal distribution for short-duration PMP. To estimate the critical storm duration a range of storms of durations ranging from 15 minutes to 6 hours are run through the model. The peak flow resulting from each of the storms is calculated and the storm duration producing the greatest flow to the catchment outlet is nominated as the critical storm duration. No methods are currently available to estimate rainfall intensities for storms with a duration greater than 6 hours. Hence the critical duration was assumed to be 6 hours in the instance where no one storm duration up to 6 hours proved outright to be the critical storm.

Australian Rainfall & Runoff, 1987 (AR&R) recommends that all catchment characteristics in the formulated models are identical to the "calibrated" catchment, except for the rainfall losses. Storm losses for the estimation of the PMF are recommended to be equal to or possibly a little less than the minimum value in large floods observed for the catchment, with suggested design losses of 0 mm initial loss and 1 mm/hr deemed reasonable unless other data indicates otherwise.

The RAFTS model can be used without changes to the *m* value (*which is the exponent value in the power law storage-discharge relation*) especially with small flood plains, but the PMF is likely to be overestimated to some extent. This overestimation is not quantifiable. As no better alternative method of PMF estimation is readily available the results of the RAFTS simulation for PMF were adopted.

No account was taken of an adjustment to the hydrograph peak to allow for the faster movement of this extreme flood through the stream system, as there is no reliable flow data for significant flooding events available to indicate the flood behaviour.

8.1.3 Hydrologic Modelling Results

Peak Discharges

Peak tributary catchment discharges determined using the RAFTS hydrologic model are listed in **Table 13**. The peak discharges are referenced to the RAFTS model node identifiers, which can be located in **Figure 7**. For example, the peak discharge in Turallo Creek at the upstream end of Bungendore village, corresponds to the listed discharges in **Table 13** for RAFTS model node number **1.07**. As shown in **Figure 7**, this peak discharge is for all catchment runoff draining to the upstream end of the town. Modelling indicated a peak PMF discharge of 2,091 m^3/s, at the Kings Highway crossing of Turallo Creek.

Table 13 PEAK FLOWS BASED ON 6 HOUR CRITICAL STORM DURATION

RAFTS MODEL NODE NUMBER	PEAK DISCHARGE (*m^3/s*)				
	PMF	100 year ARI	50 Year ARI	20 year ARI	5 year ARI
1.00	696	94.2	80.7	68.4	47.5
1.01	1,049	132.5	115	97.9	70.4
1.02	1,503	180.5	157	133	96.9
1.03	1,688	212	185	157	113
1.04	1,909	242	211	179	129
1.05	124.5	21.0	18.2	15.7	11.2
1.07	2,091	261	229	193	138
2.01	802	72.1	62	52.4	36.7
2.02	1,370	133	115	96.5	67.8
2.03	1,585	161	140	117	82.8
3.01	573	63.8	54.9	45.4	31.7
3.02	224	28.9	25.0	20.6	14.5
3.03	797	92.1	79.3	65.4	45.7
3.04	802	93.1	80.2	66.2	46.2
3.05	178	24.2	21.0	17.1	12.1
3.07	382	48.0	41.7	33.9	24.1
3.09	132	27.4	23.9	21.5	15.4
3.10	1,226	43.8	38	31	22
4.01	549.5	54.2	46.9	38.8	27.0

*NB For node and catchment locations refer to **Figure 7**.*

In addition, discharge hydrographs for each of the major tributaries within the catchment (*viz., Turallo, Halfway and Millpost Creeks*) are enclosed in **Appendix F**.

Discussion

As discussed in previously, it is customary to calibrate hydrologic models to recorded streamflow data for major historic floods (*such as the 1956 or 1974 floods*). However, in situations where there is insufficient 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 is based on 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 each of the Turallo, Brookong, and Millpost Creek catchments and used as a sensitivity check on the peak discharges generated using the RAFTS model. The comparison is provided in **Table 14**. It shows that the RAFTS model generally predicts higher discharges than the PRM, particularly in larger storm events.

Nonetheless, on the basis of the results presented, it can be concluded that the RAFTS model generates realistic estimates of peak discharges from the catchment for the 100 year and 20 year ARI events.

Table 14 COMPARISON OF RAFTS AND THE RATIONAL METHOD PEAK DISCHARGES

LOCATION	RAFTS MODEL NODE NUMBER	RAFTS MODEL (m^3/s)		t_c (hours)	RATIONAL METHOD (m^3/s)		t_c (hours)
		100 yr ARI	20yr ARI		100 yr ARI	20yr ARI	
Kings Highway Crossing of Turallo Creek	1.07	261.4	192.7	6	283.3	170.1	
Millpost Creek	3.05	159.2	117.4	6	141.6	88.6	
Halfway Creek (*upstream of Tucking Yard Lane*)	2.03	161.1	117.1	6	159.2	99.6	

8.2 HYDRAULIC MODELLING

The product of the hydrologic modelling was a set of inflow hydrographs for each of the five identified input points to the hydraulic model. Each set comprised of the 100, 50, 20 and 5 year ARI and PMF flow hydrographs. The locations of these hydrographs are identified in **Figure 9**. RMA-2 also requires a level hydrograph at the outlet of the model. The calculation of these tailwater levels is described in **Section 7.3**.

8.2.1 Design Simulations

The RMA-2 hydrodynamic model of the three creeks in the vicinity of the village, was used to simulate flood behaviour through Bungendore for the design 100, 50, 20, and 5 year ARI events, and the probable maximum flood.

Upstream boundary conditions were defined by inflow hydrographs developed using the RAFTS hydrologic model (*refer* **Section 6**). For example, the design 100 year ARI 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. Adopted hydrographs for the 100 year ARI flood are enclosed in **Appendix F**. The downstream boundary condition was based on stage hydrographs developed by applying a normal depth calculation at the downstream model boundary

8.2.2 Results

Events Up to and Including the 100 Year Recurrence Flood

Data from the model outputs was also plotted as a longitudinal water surface profile along the length of Turallo Creek extending from above the railway bridge crossing to the confluence with Millpost Creek. The profile of floodwater surfaces is presented in **Figure 14**.

The hydraulic modelling provided design floodwater levels, floodwater depths and flow velocities across the area covered by the hydraulic model, for each of the flood frequencies considered. Separate plots of water depth contours across the study area and of the extent of flooding are presented in **Figures 15** to **22** for each of these events.

Peak flood levels at key locations for each design flood event are listed in **Table 15** for each model cross-section.

Please note that the model network and all RMA modelling results files have been provided in a digital format on CD-ROM to Council and DLWC. All flood behaviour patterns and flood characteristics can be interrogated readily with the accompanying Patterson Britton viewing package.

Table 15 PREDICTED PEAK DESIGN FLOOD LEVELS AT KEY LOCATIONS WITHIN THE VILLAGE

LOCATION	PREDICTED PEAK FLOOD LEVEL (*m AHD*)				
	5 year ARI	20 year ARI	50 year ARI	100 year ARI	PMF
Turallo Creek upstream of railway line bridge crossing	692.9	693.3	693.4	693.6	695.7
Turallo Creek upstream of Tarago Road Bridge	690.2	690.4	690.7	691.0	694.6
Upstream of confluence of Turallo Creek and Halfway Creek	689.9	690.1	690.7	691.0	694.6
Downstream of confluence of Turallo Creek and Halfway Creek	689.7	690.0	690.7	690.9	694.6
Halfway Creek upstream of Gundaroo Road Bridge	690.2	690.3	690.7	691.0	694.6
Upstream of confluence of Turallo Creek and Millpost Creek	689.7	690.0	690.6	691.0	694.6
Downstream of confluence of Turallo Creek and Millpost Creek	689.7	690.0	690.6	690.9	694.6

8.2.3 Discussion

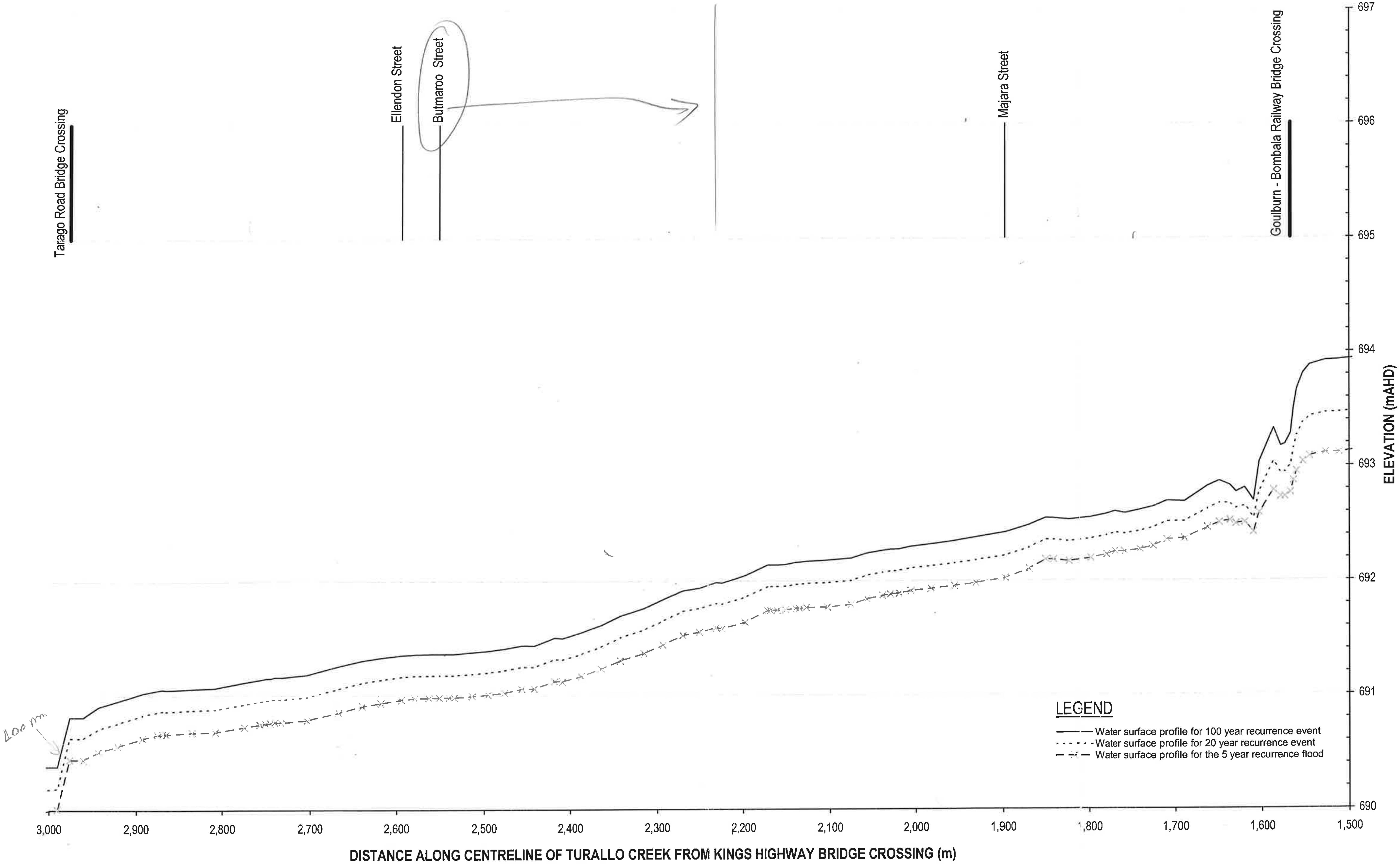
The flood profile, shown in **Figure 14**, is a 'good fit' to 1974 known flood marks. The 1974 event is generally below the 100 year ARI event and appears to be close to a 50 year or 20 year ARI event. The modelled design affluxes across the bridges are supported by the 1974 floodmarks.

For the smaller flood events, of 20 year and 5 year ARI, along Turallo Creek, upstream of the Halfway confluence, there is localised flooding over the river banks, without overtopping of the levee system. Upstream of the railway embankment a considerable area of land on the right bank floods. With the additional flows of Halfway Creek and Millpost Creek further downstream more substantial flooding occurs. As a result of the Turallo-Halfway confluence an overland flowpath is created by the Turallo floodwaters which circumvents the junction .The inflow from Millpost Creek is especially problematic with both backwater flooding on the left bank of Turallo and a large tract of breakout flow over the right bank. Areas of the town centre also experience flooding including Ellendon Street. Scattered incidents of flooding also occur along Halfway Creek, particularly upstream of the Bungendore Road Bridge with flooding of the right bank. Approximately 1 km upstream of the Bungendore Road crossing of Millpost Creek some overtopping to the relatively flat floodplain occurs. The lowlying floodplain extending between Halfway Creek and Millpost Creek also floods, particularly in the vicinity of Trucking Yard Lane.

The more severe 100 year and 50 year recurrence events show mostly an exacerbation of the flooding behaviour of the lesser events. The extent of flooding along Turallo Creek increases with overtopping of the town-centre levee system with flooding evident along Ellendon, Molonglo and Gibraltar Streets. All land north of Bungendore Road is severely inundated. The pasturelands along the left bank of Millpost Creek approximately 1 km upstream of the Gundaroo Road crossing are also substantially flooded.

PMF conditions see the vast portion of the study area inundated, with the entire town-centre affected. As with lesser floods the land in the vicinity of creek confluences is extremely inundated to great depth, including Elmslea Estate.

FIGURE 14



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rp3958 - Elmslea Flood Impact Assessment
3958 Water Surface Profile (Turallo Ck).xls
WS Profile Plot

PEAK FLODWATER SURFACE PROFILE FOR THE VILLAGE REACH OF TURALLO CREEK

FIGURE 16

Patterson Britton & Partners Pty Ltd
J 2722 / R 1913
FIGURE-5yr_EXT.DGN

EXTENT OF INUNDATION DURING THE 5 YEAR RECURRENCE EVENT

FIGURE 17

Patterson Britton
& Partners Pty Ltd
J 2722 / R 1913
FIGURE-20yr_cont.DGN

CONTOURS OF PEAK FLOODWATER LEVEL FOR THE 20 YEAR RECURRENCE EVENT

Patterson Britton & Partners Pty Ltd

J 2722 / R 1913
FIGURE-20yr_EXT.DGN

EXTENT OF INUNDATION DURING THE 20 YEAR RECURRENCE EVENT

CONTOURS OF PEAK FLOODWATER LEV
FOR THE 100 YEAR RECURRENCE EVE

EXTENT OF INUNDATION DURIN
THE 100 YEAR RECURRENCE EVEN

Patterson Britton & Partners Pty Ltd J 2722 / R 1913 FIGURE-20yr_cont.DGN

The first of these shows approximate relationships between the depth and velocity of floodwaters and resulting hazard. This relationship has been used to define the provisional low and high hazard categories represented in the second of these plots.

9.2 ADOPTED HAZARD CATEGORISATION

As shown above, flood hazard is a measure of the degree of difficulty that pedestrians, cars and other vehicles will have in egressing flooded areas, and the likely damage to property and infrastructure. At low hazard, passenger cars and pedestrians (*adults*) are able to move out of a flooded area. At high hazard, wading becomes unsafe, cars are immobilised and damage to light timber-framed houses would occur.

Flood hazard is categorised according to a combination of the flow velocity and the depth of floodwater. The categories are defined by lower and upper bound values for the product of flow velocity and floodwater depth.

Spatial and temporal distributions of flow, velocity and water level determined from the computer modelling undertaken as part of this study, were used to determine the flood hazard along Bellbird and Lavender Creeks. Interpretation of this data indicates that for large events like the 1% AEP flood, most areas of flooded land would fall within the high hazard category defined in the *'Floodplain Management Manual'* (*2001*).

Hence, for the purpose of understanding how the flood hazard affects existing development and areas of potential future development, it is useful to further subdivide areas falling within the high hazard category, into High Hazard, Very High Hazard and Extreme Hazard. Similarly, the low hazard category defined in the manual has been subdivided to create a Low Hazard and a Medium Hazard category.

Each of these categories and their relationship between depth of inundation and water velocity is shown in **Table 16.**

Table 16 ADOPTED HAZARD CRITERIA

HAZARD CATEGORY	CRITERIA
Low	Depth (d) < 0.4 m & velocity (v) < 0.5 m/s
Medium	exceeding Low criteria, and $d \leq 0.8$ m, $v \leq 2.0$ m/s, and $v \times d \leq 0.5$
High	exceeding Medium criteria, and $d \leq 1.8$ m, $v \leq 2.0$ m/s, and $v \times d \leq 1.5$
Very High	exceeding High criteria, and with 0.5 m/s < velocity < 4 m/s & $v \times d \leq 2.5$
Extreme	exceeding Very High criteria and v > 0.5 m/s

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& Partners Pty Ltd

J 2722 / R 1913
FIGURE-100yr_EXT.DGN

EXTENT OF INUNDATION DURING THE 100 YEAR RECURRENCE EVENT

FIGURE 21

CONTOURS OF PEAK FLOODWATER LEVEL FOR THE PMF

Patterson Britton & Partners Pty Ltd J 2722 / R 1913 FIGURE-PMF_cont.DGN

9 FLOOD HAZARD CATEGORISATION

9.1 FLOOD HAZARD

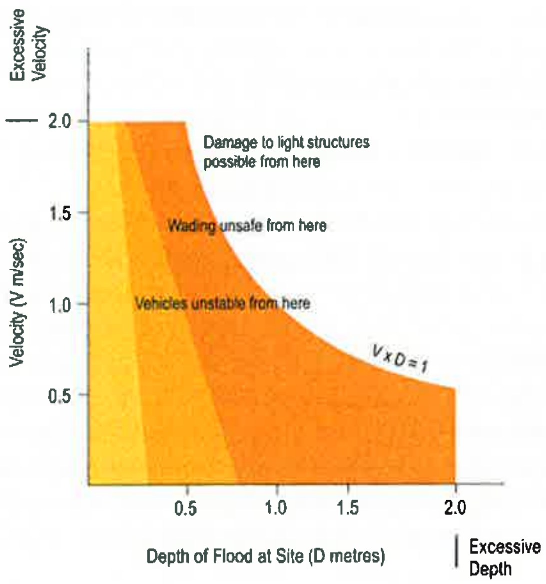
The personal danger and physical property damage caused by a flood varies both in time and place across the floodplain. Accordingly, the variability of flood patterns across the floodplain over the full range of floods, needs to be understood by flood prone landholders and by floodplain managers.

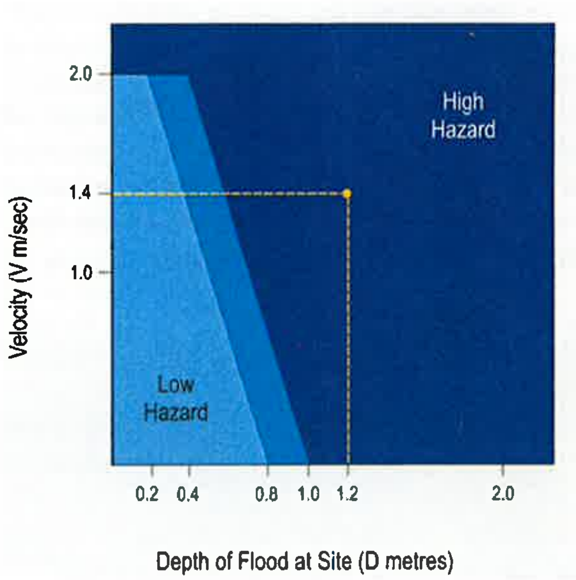
Representation of the variability of flood hazard across the floodplain provides floodplain managers with a tool to assess the existing flood risk and to determine the suitability of land use and future development. The hazard associated with a flood is represented by the static and dynamic energy of the flow, which is in essence, the depth and velocity of the floodwaters. Therefore, the flood hazard at a particular location within the floodplain, is a function of the velocity and depth of the floodwaters at that location.

The NSW Government's *'Floodplain Management Manual'* (*2001*), characterises hazards associated with flooding into a combination of three hydraulic categories and two hazard categories. Hazard categories are broken down into 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

As a result, the manual effectively divides hazard into two categories, namely, high and low. An interpretation of the hazard at a particular site can be established from the following graphs, which have been taken directly from the manual.





The first of these shows approximate relationships between the depth and velocity of floodwaters and resulting hazard. This relationship has been used to define the provisional low and high hazard categories represented in the second of these plots.

9.2 ADOPTED HAZARD CATEGORISATION

As shown above, flood hazard is a measure of the degree of difficulty that pedestrians, cars and other vehicles will have in egressing flooded areas, and the likely damage to property and infrastructure. At low hazard, passenger cars and pedestrians (*adults*) are able to move out of a flooded area. At high hazard, wading becomes unsafe, cars are immobilised and damage to light timber-framed houses would occur.

Flood hazard is categorised according to a combination of the flow velocity and the depth of floodwater. The categories are defined by lower and upper bound values for the product of flow velocity and floodwater depth.

Spatial and temporal distributions of flow, velocity and water level determined from the computer modelling undertaken as part of this study, were used to determine the flood hazard along Bellbird and Lavender Creeks. Interpretation of this data indicates that for large events like the 1% AEP flood, most areas of flooded land would fall within the high hazard category defined in the *'Floodplain Management Manual'* (*2001*).

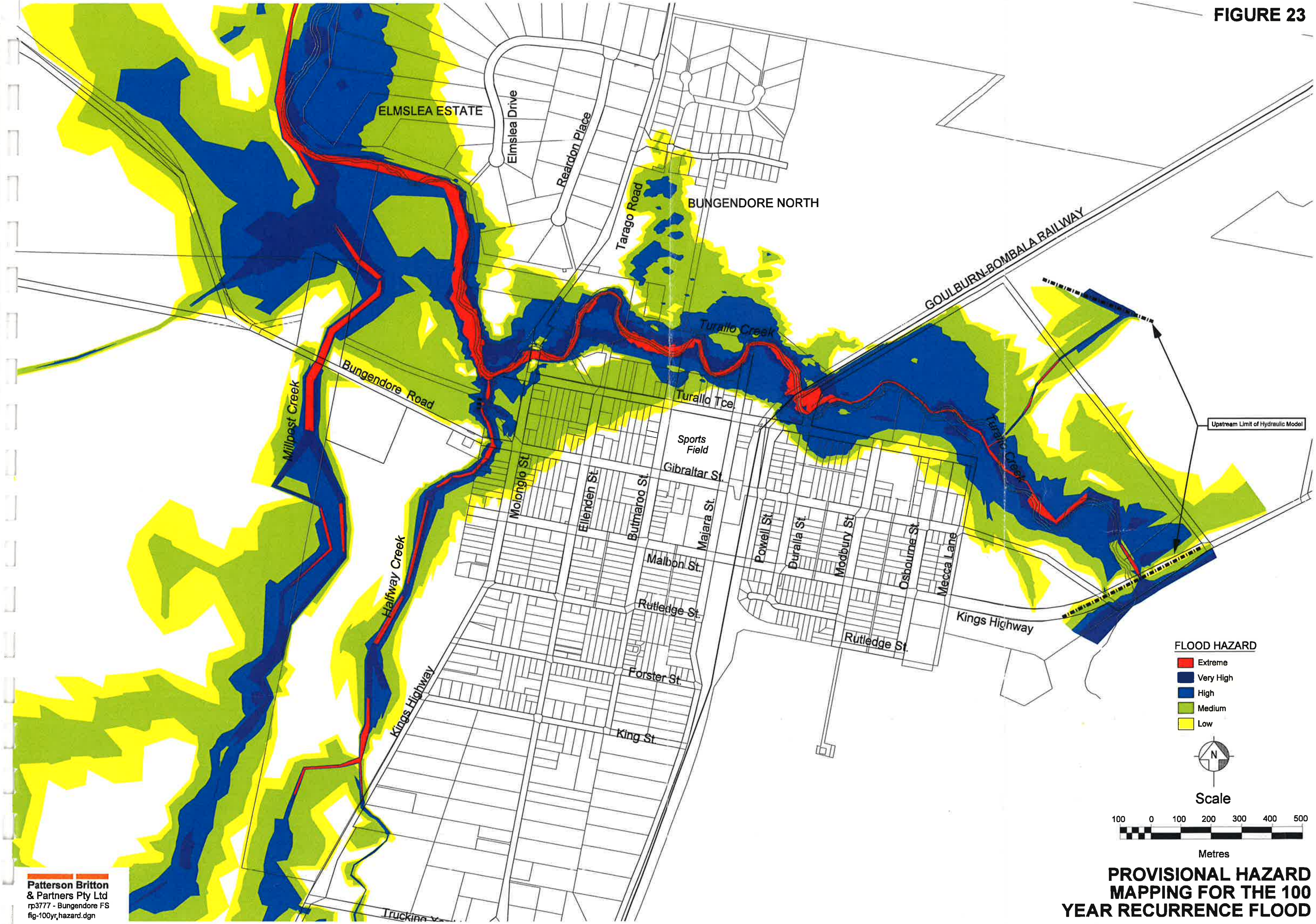
Hence, for the purpose of understanding how the flood hazard affects existing development and areas of potential future development, it is useful to further subdivide areas falling within the high hazard category, into High Hazard, Very High Hazard and Extreme Hazard. Similarly, the low hazard category defined in the manual has been subdivided to create a Low Hazard and a Medium Hazard category.

Each of these categories and their relationship between depth of inundation and water velocity is shown in **Table 16.**

Table 16 ADOPTED HAZARD CRITERIA

HAZARD CATEGORY	CRITERIA
Low	Depth (d) < 0.4 m & velocity (v) < 0.5 m/s
Medium	exceeding Low criteria, and $d \leq 0.8$ m, $v \leq 2.0$ m/s, and $v \times d \leq 0.5$
High	exceeding Medium criteria, and $d \leq 1.8$ m, $v \leq 2.0$ m/s, and $v \times d \leq 1.5$
Very High	exceeding High criteria, and with 0.5 m/s < velocity < 4 m/s & $v \times d \leq 2.5$
Extreme	exceeding Very High criteria and $v > 0.5$ m/s

FIGURE 23



PROVISIONAL HAZARD MAPPING FOR THE 100 YEAR RECURRENCE FLOOD

Patterson Britton & Partners Pty Ltd
rp3777 - Bungendore FS
fig-100yr.hazard.dgn

9.3 PROVISIONAL FLOOD HAZARD

The criteria presented in **Table 16** were used to determine the provisional flood and hazard mapping along Turallo Creek. Results from the computer modelling completed for this study were combined with this hazard category criteria to generate provisional flood hazard mapping for the design 100 year recurrence flood. Mapping showing the flood extent and the variability in flood hazard is presented in **Figure 23**. The limit of the low hazard area effectively defines the flood extent.

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 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.

Accordingly, modification of the hazard mapping presented in **Figure 23**, may occur during the investigations required to develop a Floodplain Risk Management Plan for the area.

10 REFERENCES

(1) Australian Bureau of Statistics, 1996 Census

(2) AUSTROADS (*1994*), *'Waterway Design – A Guide to the Estimation of Bridges, Culverts and Floodways'*; AUSTROADS Publication No AP-23/94, ISBN 0 85588 440 1.

(3) Bradley JN (*1978*), *'Hydraulics of Bridge Waterways'*; prepared for the US Department of Transportation / Federal Highway Administration.

(4) Bureau of Meteorology (*1994*), *'Bulletin 53 - The Estimation of Probable Maximum Precipitation in Australia: Generalised Short-Duration Method'*; Australian Government Publishing Service, ISBN 0 644 33419 3.

(5) Chow VT(*1959*), *'Open Channel Hydraulics'*; published by McGraw Hill (Reissued 1988) ISBN 07 010776 9.

(6) Institution of Engineers (*1987*), *'Australian Rainfall and Runoff – A Guide to Flood Estimation'*; edited by DH Pilgrim, ISBN 085825 434 4.

(7) JD Kilmartin Pty Ltd (*1992*), *'Elmslea Estate, Bungendore – Flood Study'*; prepared by Boyden & Partners Pty Ltd.

(8) King IP (*1997*), *'RMA-2 User Manual'*

(9) NSW Government (*2001*), *'Floodplain Management Manual: the Management of Flood Liable Land'*; ISBN 07313 0370 9.

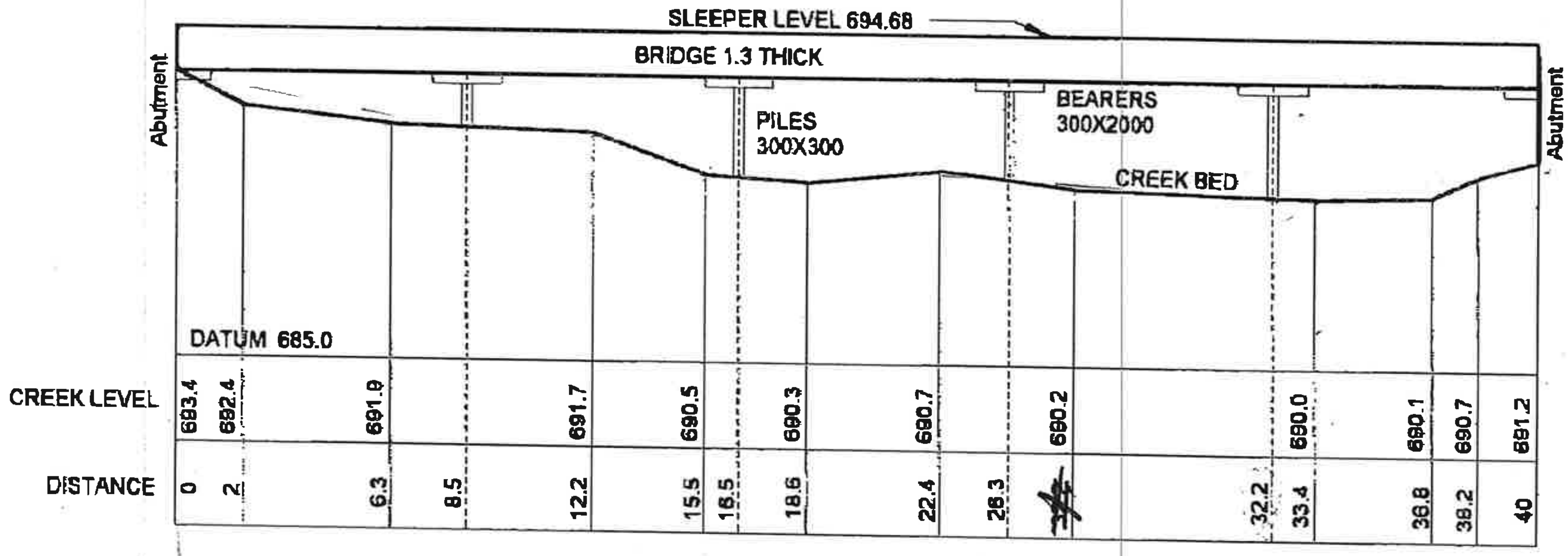
(10) Yarrowlumla Shire Council (*1976*), *'Bungendore Flood Mitigation Study'*; prepared by DN Foster & B Le Plastrier of the UNSW Water Research Laboratory; Technical Report No 76/1.

(11) US Army Corp of Engineers, Hydrologic Engineering Centre (*April, 1997*), *'HEC-RAS River Analysis System – Hydraulic Reference Manual'*; also incorporating HEC-RAS software.

(12) WP Software (1992), *'Runoff Analysis & Flow Training Simulation, RAFTS-XP Manual, Version 2.80'*

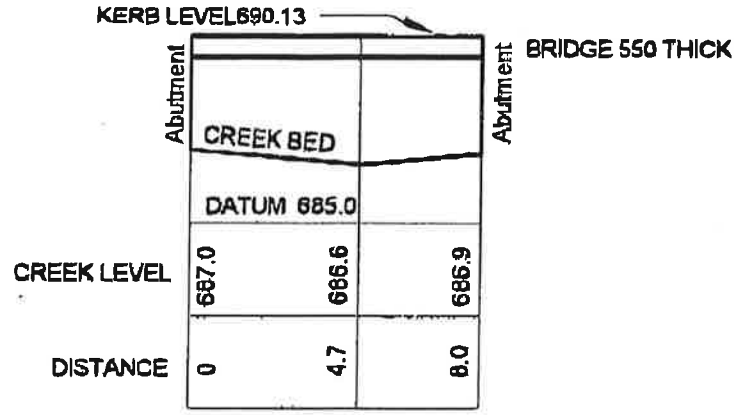
(13) Yarrowlumla Shire Council (*1997*), *'Interim Flood Policy for the Village of Bungendore'*

APPENDIX A
DETAILS OF BRIDGE CROSSINGS OF TURALLO AND HALFWAY CREEKS



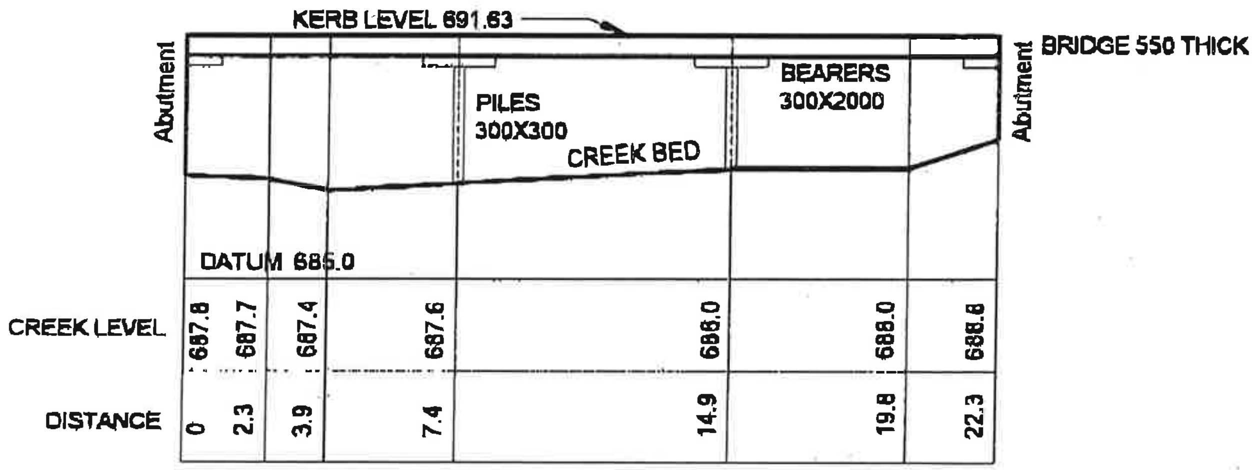
RAIL BRIDGE OVER TURALLO CREEK
LOOKING UPSTREAM
Scale 1:200

Surveyed Ken Bromley
September 1996
Bungendore Flood Study



Bungendore

GUNDAROO RD BRIDGE OVER HALFWAY CREEK
LOOKING UPSTREAM
Scale 1:200



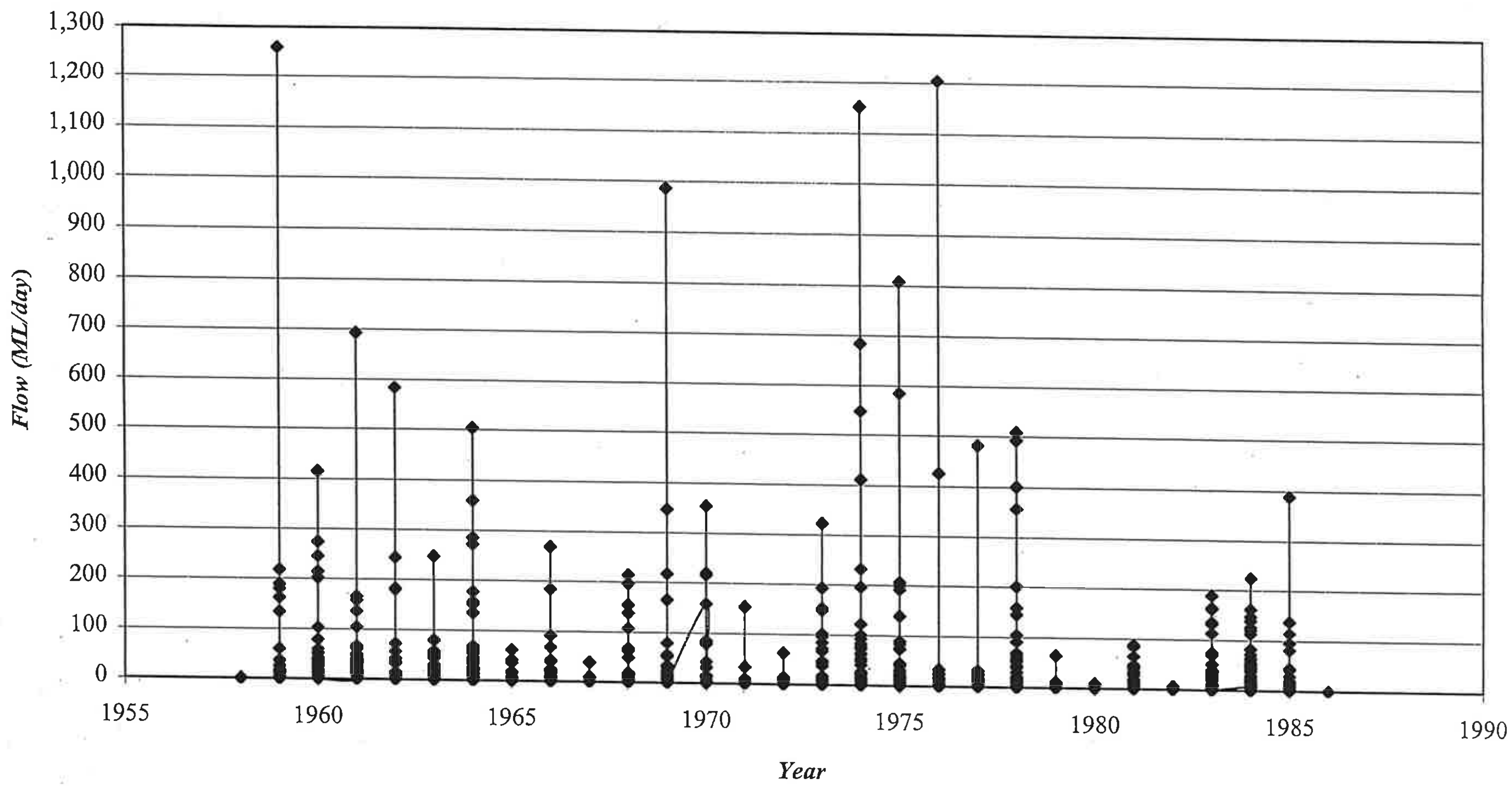
TARAGO RD BRIDGE OVER TURALLO CREEK
LOOKING UPSTREAM
Scale 1:200

Surveyed Ken [illegible]
September [illegible]
Bungendore Flood Study

APPENDIX B
STREAMFLOW RECORDS FOR GAUGES ALONG MILLPOST AND TURALLO CREEKS

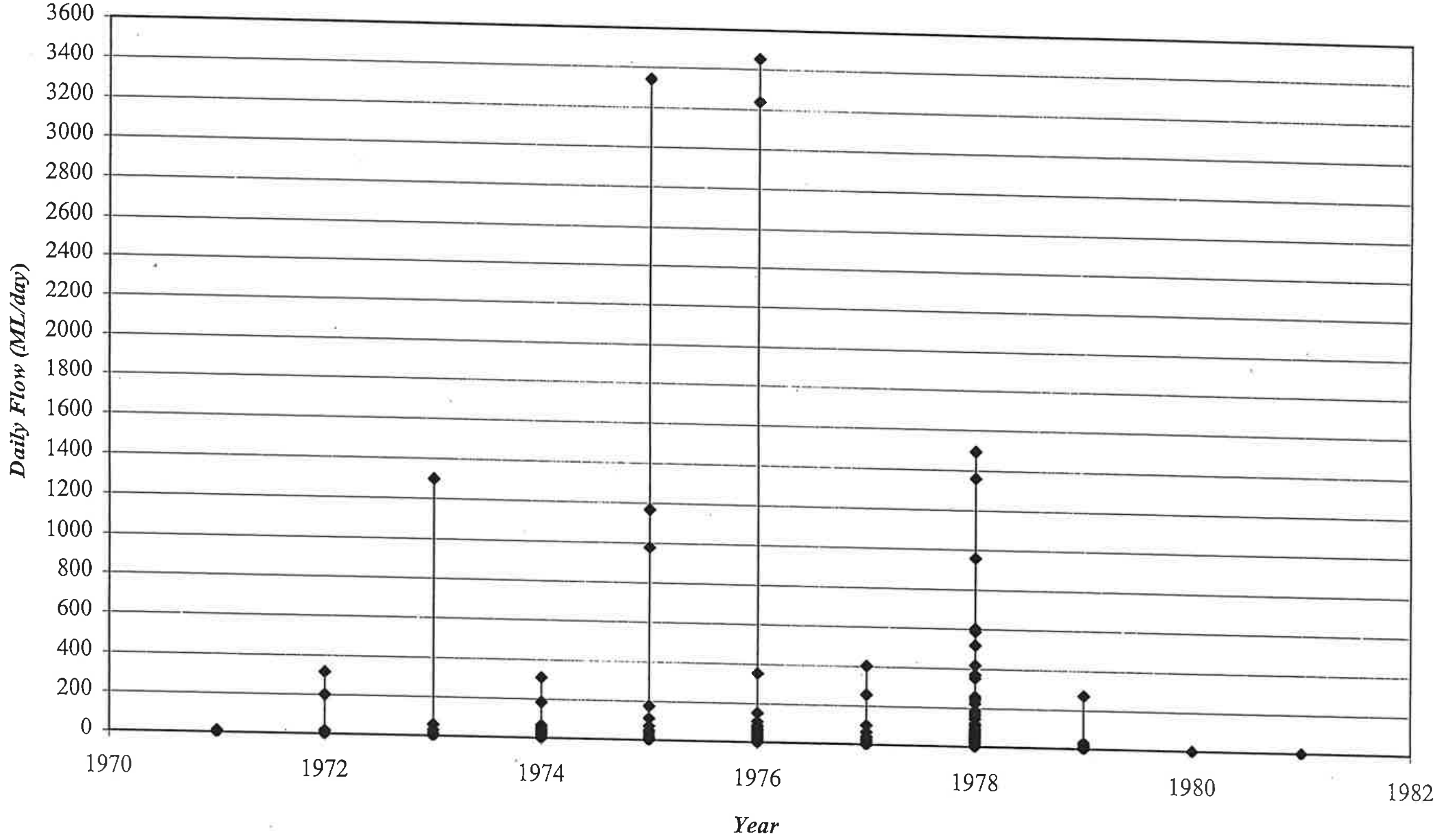
MILLPOST FLOW GAUGE *411001*

Summary of Daily Flows



TURALLO FLOW GAUGE *411002*

Summary of Daily Flows



APPENDIX C
HYDROLOGIC MODEL PARAMETERS

SUB-CATCHMENT MODEL PARAMETERS

Sub-catchment Node	Area (ha)	Vector Averaged Slope (%)	Pervious 'n'	Initial Loss (mm)	Continuing Loss (mm/hr)
1.01	2,009	5.1	0.08	0	1.9
1.02	955	7.9	0.08	0	1.9
1.03	1,165	5.4	0.09	0	1.9
1.04	967	2.9	0.09	0	1.9
1.05	1,120	4.4	0.07	0	1.9
1.06	349	3.5	0.07	0	1.9
1.07	741	9.4	0.07	0	1.9
2.01	1,542	3.5	0.07	0	1.7
2.02	1,497	2.0	0.07	0	1.7
2.03	802	1.6	0.06	0	1.7
3.01	1,138	4.2	0.07	0	1.7
3.02	421	5.0	0.08	0	1.7
3.04	34	21.1	0.06	0	1.7
3.05	382	4.0	0.07	0	1.7
3.07	670	5.5	0.07	0	1.7
3.09	312	11.7	0.07	0	1.7
3.10	540	9.3	0.08	0	1.7
4.01	802	1.7	0.06	0	1.9

ESTIMATION OF PROBABLE MAXIMUM RAINFALL INTENSITY

The estimation of the probable maximum rainfall (*PMP*) involves a number of steps as described in the Bureau of Meteorology publication *Amended Bulletin 53 – The Estimation of Probable Maximum Precipitation in Australia: Generalised Short-Duration Method.* This methodology, as applied to the Bungendore catchment, can be summarised as follows:

- A scaled spatial distribution diagram was placed over a figure of the catchment that included the delineation of the hydrologic sub-catchments. The distribution diagram was placed so as to contain the catchment within the smallest possible ellipse – in this instance *Ellipse F* (*see the attached figure*).
- The catchment area between successive ellipses were measured and thus, the area enclosed by each ellipse were estimated.
- The relationship between catchment area and rainfall depth for various rainfall durations is produced in a graphical format in *Bulletin 53*. The initial mean rainfall depth enclosed by each ellipse was estimated with the use of this graph.
- These estimated rainfall depths were then adjusted for both moisture and elevation.
- The volume of rainfall enclosed by each ellipse was calculated and hence the volume of rainfall between the successive ellipses.
- The mean rainfall depth between successive ellipses was then obtained by dividing the rainfall volume between ellipses by the area between ellipses.
- Due to the construction of the RAFTS hydrologic model estimations of rainfall intensities were required. These estimations for the various rainfall durations are tabulated below *e.g. the mean rainfall intensity over a 6 hour duration between ellipse B and ellipse C is estimated to be 96 mm/hr.*
- The formulated model was run for each storm duration to identify the critical duration. For each model run the rainfall intensity for each sub-catchment was assigned individually, using the table below *e.g. for sub-catchment 3.05 the rainfall intensity of 6 hour duration is 79 mm/hr.*

PMP Mean Rainfall Intensity Between Ellipses (mm/hr)

Ellipse	Storm Duration (hours)										
	0.25	0.5	0.75	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0
A	585	423	357	311	267	234	207	189	162	143	126
B	502	373	316	279	236	208	184	167	144	126	112
C	437	319	269	244	230	181	163	146	124	109	96
D	379	274	235	212	168	160	146	133	110	97	86
E	340	259	216	202	173	148	134	124	104	90	79
F	334	185	206	187	158	148	136	114	100	83	74