2003

Fluvial geomorphology of the Nambucca river catchment: late quaternary change, post-settlement channel degradation and proposals for rehabilitation

Christopher J. Doyle
University of Wollongong

FLUVIAL GEOMORPHOLOGY OF THE NAMBUCCA RIVER CATCHMENT:
LATE QUATERNARY CHANGE, POST-SETTLEMENT CHANNEL DEGRADATION AND PROPOSALS FOR REHABILITATION

A thesis submitted in fulfilment of the requirements for the award of the degree

DOCTOR OF PHILOSOPHY

from

University of Wollongong

by

Christopher J. Doyle

B.Env.Sc (Hons) Land Resources

School of Geosciences

2003

CERTIFICATE OF ORIGINALITY

I, Christopher J. Doyle, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Geosciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

(Signed)......

Christopher J. Doyle   June 23, 2003

ACKNOWLEDGEMENTS

Most sincere thanks must go to Professor Gerald Nanson for giving me the opportunity to undertake this study. His friendship, ideas and guidance have been of immense value. My understanding of rivers has much to do with his insight and dedication to the field.

I must also extend the most special of thanks to my wife Ulla-Maija. On the day this project commenced I did not know her at all and in the time since she has become my girlfriend, fiancée, and now beloved wife of five years. Her assistance and motivation has been a force behind this completed work.

I must also thank the field assistants I have had over the life of the project, especially Richard Walsh, Maria Coleman, Steven Tooth, Geoff Black, Tim Cohen, Ulla-Maija Doyle and Rob Storrs. Between us all we drove over 20,000 km, ventured onto more than 50 different properties, completed 15 km of surveying, sieved 1.5 tonnes of sediment, measured the dimensions of 3600 stones, examined 42 river rehabilitation works and augured or drilled through almost 1 km of sediment! Many thanks also to David Price and Jose Abrantes for their analysis of the TL samples.

I would like to extend my gratitude to Steve Perrens and his consulting staff for assistance in collating land use and hydrology data. Thanks also to Andrew Brooks for his assistance with the project and his perceptions and expertise in the area of riparian vegetation. He was the inspiration behind the vegetation chapter of this thesis. I would also like to thank the residents of the Nambucca Shire for opening their gates and their homes and for passing on the knowledge they have gained.

My penultimate thank you goes to my family. To mum and dad for their unconditional support, love and prayers, and to my sisters Angela, Gabrielle, Loretta, Louise and Collette and their families for their consideration.

Finally, I have been much blessed during the undertaking of this work. Thanks and credit go to Him who has guided me and answered so many prayers.

ABSTRACT

The Nambucca River catchment is on the mid-north coast of New South Wales, Australia, and drains 1,407 km^2 of land east of the Great Dividing Range. This study examines the pre- and post-settlement record of channel change in the seven tributaries of the Nambucca catchment and suggests a scheme for rehabilitation based on current geomorphic information and the identified record of channel changes.

The Late Pleistocene history, obtained from 19 river terrace thermoluminescence dates, identifies a remnant terrace of 78 ka from the Colleambally Phase during Oxygen Isotope Stage (OIS) 5. Younger terraces correspond to the Kerarbury Phase (55-35 ka) and the Gum Creek Phase (31-25 ka), both in OIS 3. However, the majority of terraces date during the Yanco Phase (20-13 ka) in OIS 2. This record of late Quaternary activity correlates with periods of fluvial activity identified on the much larger Nepean and Murrumbidgee Rivers in southeastern Australia. No sediment dates have been obtained in the Nambucca catchment for the period 12 ka to 3 ka, probably because extensive flushing removed most of that alluvium in what has recently been termed the Nambucca Phase. Radiocarbon dating of the Nambucca floodplains has provided 15 dates, all but one younger than 3000 yrBP. Between 3000 and 2500 yrBP, the streams changed from gravel, braided and somewhat laterally active, to stable systems forming floodplains by vertical accretion and with channels that underwent occasional avulsion. This laterally stable period continued through to European settlement in the middle 1800's.

Since settlement there have been four periods of change in the catchment that have shaped the formation of the streams in the catchment:

Phase 1 (1830-1870): Settlers selectively logged the forested catchments for red cedar (*Toona australis*) but during this phase much of the forest on stream banks and floodplains remained intact.

Phase 2 (1870-1896): Extensive land clearance for agriculture occurred during this phase. A cluster of large floods in the 1890's triggered a series of nickpoints. The initial channel instability problems probably date to this period.

Phase 3 (1897-1947): The period from the late 1890's to the late 1940's was relatively dry with very few recorded flood events. However, the earliest available aerial photographs from 1942 indicate channels straightened with meanders having cut-offs in the lower part of the catchment. The catchment appears to have been primed for major change during the flood dominated phase after 1947.

Phase 4 (1948-Present): The change to this phase was associated with a series of large floods in the late 1940's and early 1950's. Streams experienced substantial bed lowering, continual overwidening and the exposure of abundant floodplain sediment, releasing massive amounts of gravel that had been stored for 3,000 years. The exposed gravel bars soon became colonised by *Casuarina cunninghamiana*, which many landholders believed worsened the problems of channel instability in the catchment. In an effort to restore the streams, government authorities from the 1960's to 1980's encouraged the extraction of gravel and the removal of woody debris from the streams.

This investigation of the modern Nambucca catchment identifies tributaries floored with fine quartz gravel, migrating nickpoints, large colonies of *Casuarina cunninghamiana* and, bankfull channel capacities that can now convey 1-in-10-year floods and greater. An assessment of catchment geomorphology, and review of the many river rehabilitation schemes that have been attempted, recommends that controlling bed levels is a high priority. In this catchment substantial government funding is unlikely and the use of 'soft' engineering methods are required to provide longer term benefits for river rehabilitation. The construction of rock ramps appears to be the most suitable method for setting bed levels and arresting nickpoint retreat. Other methods such as pin groynes, brush groynes and jacks have all proven successful in straight reaches experiencing overwidening and bank retreat. Importantly, effective management of the riparian zone is required to encourage growth of native vegetation species in the absence of livestock.

This study provides a comprehensive review of changes in catchment behaviour from the late Quaternary to the modern day; it provides detailed information about the geomorphology and sedimentology of the channels, and it completes a detailed assessment of rehabilitation schemes. As such it presents stream managers with a methodology for making scientifically based decisions on river rehabilitation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Introduction

The streams of the middle and northern coast of New South Wales (NSW) in Australia have been studied extensively without resolving clearly the impact of European settlement on fluvial activity. This study of the Nambucca River catchment examines in detail the climate and flow regime changes occurring during the late Quaternary and also assesses the impacts and timing of anthropogenic influences following European settlement. This knowledge has been used to examine the suitability of present river management practices.

The name Nambucca dates from 1835 and comes from the Aboriginal name *ngambukka,* which has been translated as meaning 'winding or crooked river' (Townsend, 1993). The 1407 km^2 Nambucca River catchment is situated on the mid-north coast of NSW (Figure 1.1). It is bordered by the Macleay catchment to the south and west, and the Bellinger catchment to the north. The headwaters drain the Great Dividing Range on the western boundary of the catchment where elevations reach 1013 metres above sea level (m.a.s.l.) at Killiekrankie Mountain. Peaks of up to 800 m.a.s.l. are found on the catchment borders. Bowra Sugarloaf (875 m.a.s.l.) is the only peak over 800 m not on the catchment boundary (Figure 1.1). Over 50% of the slopes within the catchment are classified as *steep* (8°-15°) or *rugged* (>15°) (Raine, 1994) and the western or headwater areas are the most rugged, consisting of densely timbered slopes and peaks. Further east the valley floors increase in width as the slopes decline (often cleared for agriculture) resulting in topography more undulating than steep. Towns within the catchment include Nambucca Heads, Macksville, Taylors Arm and Bowraville.

Over the past century or more the tributaries of the Nambucca River catchment have been severely degraded as illustrated by substantial bed and bank erosion. Extensive data on Quaternary history, channel capacity, bed material size and floodplain structure is presented here and used to develop proposals for the geomorphic rehabilitation and management of the Nambucca catchment.

1.2 The Drainage System

The Nambucca basin is divided into four main sub-catchments; the central basin, Taylors Arm in the centre-south, Warrell Creek in the south and the smallest, Deep Creek, in the north-east (Figure 1.1). The river emerges to the sea through an estuarine mouth effectively hidden from the early maritime explorers, James Cook and Matthew Flinders, who both passed by without noticing it (Townsend, 1993).

The central basin of the Nambucca River catchment drains 475 km^2 and is made up of Missabotti Creek, North Arm (the main arm of the Nambucca River), Buckra Bendinni Creek and South Arm. These streams all flow from west-to-east in a sub-parallel fashion before converging at or near Bowraville, close to the tidal limit.

The upper reaches of Missabotti Creek, Buckra Bendinni Creek and Taylors Arm are integrated as part of a much broader radial drainage system arising from a breached dome in the upper Bellinger Valley (Warner, 1981). The upper reach of Taylors Arm flows to the southeast, probably aligned along the Demon Fault, an orientation significantly different to the predominantly easterly flow of the other streams. It changes to east-north-east when the Arm reaches its namesake town, an alignment near parallel with that of the lower reaches of North Arm and South Arm. Taylors Arm is the longest stream in the basin with a total length of 69 km and a catchment area of 450 km^2. Major tributaries on Taylors Arm are Thumb Creek (40 km^2) and Bakers Creek (70 km^2). The tidal limit of Taylors Arm is at Utungun and meets the Nambucca River at Macksville, whereas North Arm and South Arm converge to form the Nambucca River, with its tidal limit near Bowraville (Figure 1.1 and Appendix 1).

Warrell Creek, in the southwest of the Nambucca catchment, is formed with the confluence of Eungai Creek and Allgomera Creek. Easterly flow changes to northerly flow around Yarrahapinni Mountain. The tidal limit is 2.5 km downstream from the Allgomera Ck confluence, and this tributary joins the Nambucca River on the coast at Nambucca Heads (Figure 1.1).

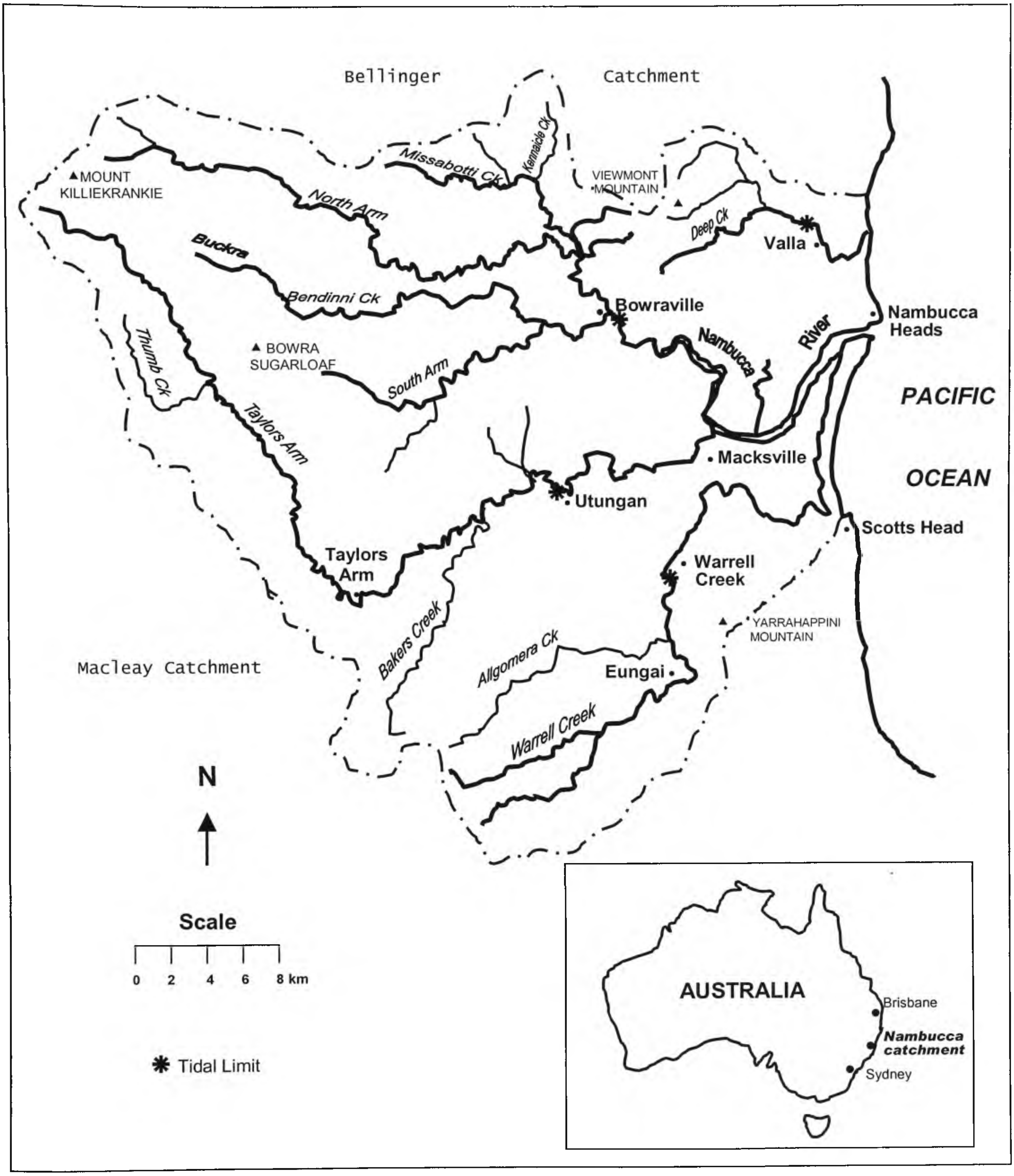


Figure 1.1: Nambucca River and catchment

Deep Creek is a small sub-catchment in the northeast draining Mount England (279m) and the low divide northeast of Bowraville in the south and Viewmont Mountain (464m) in the north. The only major tributary is Viewmont Creek and the tidal limit is 0.5 km upstream of Valla. The Deep Creek catchment is strictly not part of the Nambucca River catchment as it flows to the ocean at Valla Beach. However, it is included as it is on the Nambucca side of the well-defined ranges dividing the Nambucca/Bellingen catchments.

The total catchment area of the Nambucca catchment excluding Deep Creek is about 1,352 km^2 and is about 1,407 km^2 including Deep Creek. This study is concerned only with the non-tidal sections of the catchment approximately corresponding with the areas above the three gauging stations on the main Nambucca River, Taylors Arm and Warrell Creek. Non-tidal catchment areas are summarised in Table 1.1.

Table 1.1: Catchment areas in the Nambucca catchment above the tidal limit
(Areas taken to gauging station or creek junction)

Catchment	Approx. Area (km^2)
Missabotti Creek at junction with Nambucca River	*80*
Buckra Bendinni Creek at junction with South Arm	*90*
South Arm at junction with Nambucca River	*170*
Nambucca River and tributaries at Bowraville gauging station	430
Taylors Arm at Grays Crossing gauging station	340
Warrell Creek at Warrell Creek gauging station	200
Deep Creek at Deep Creek road	55
Total non-tidal area	**1,025**

Where Taylors Arm joins the main Nambucca River at Macksville the two catchments are approximately equal in area but fluvially are different in structure. Above Macksville, the

Nambucca River and its three tributaries drain a diamond shaped area whereas Taylors Arm drains a long and narrow catchment fed by numerous minor tributaries. In addition, Taylors Arm experiences less rainfall than the Nambucca River system (Figure 3.3). Because of these differences in catchment shape and water input there are differences in the flow regimes and the associated geomorphic processes.

1.3 History of the Study

Instability of the gravel-bed streams of the Nambucca catchment has been of major public concern since the catastrophic floods of 1949 and 1950. Since then, lateral migration, stream widening, bed-level fluctuation and the accumulation of gravel have all been cited as major indicators of a river system in disrepair (Raine, 1994; Resource Planning, 1989; Thoms, 1994; Department of Water Resources, 1994; Department of Land and Water Conservation, 1995; Water Conservation and Irrigation Commission, 1970; Water Resources Commission, 1979).

During the past 30 years there have been a number of reports by government departments regarding the streams of the Nambucca catchment. The earlier reports were based on flood mitigation works (eg. Department of Public Works, 1974; Gutteridge Haskins and Davey, 1981), river improvement works and costs (eg. Water Conservation and Irrigation Commission, 1970; Water Resources Commission, 1979) and flood history studies (eg. Department of Public Works, 1980, 1983). In the last decade, government departments and consultants have directed studies more at assessing catchment resources in relation to river preservation and/or restoration, particularly related to gravel extraction (eg. Resource Planning, 1989; Department of Water Resources, 1994; Thoms, 1994: Raine, 1994; Department of Land and Water Conservation 1995; 1996).

Resource Planning (1989) carried out a study on the gravel resources of the Nambucca River (North Arm) and Missabotti Creek. This study, although cited in subsequent reports, was heavily criticised by residents, as recognised by Thoms (1994). Amongst other omissions it failed to provide detailed measurements of the bedload size and lithology, and this was a major problem for assessing downstream changes in sediment size and problems associated with sediment erosion and transport.

As the era of Landcare arrived, with it came a new focus involving studies in the Nambucca. The emphasis on flood mitigation, which prevailed throughout the 1970's and early 1980's, was no longer evident. The new emphasis was aimed at controlling bank erosion and managing gravel deposition. Apart from several DLWC papers there were reports published by consultants (eg. Resource Planning, 1989; Thoms, 1994) examining bank erosion and the role of gravel extraction. DLWC produced papers on the importance of riparian vegetation (Raine, 1994) and provided guides for the implementation of river works that were required throughout the catchment (DLWC, 1995). All of the reports cited above called for a major scientific study to examine the cause of degradation and identify the steps involved in remedying the problem.

In November 1995 the Nambucca Total Catchment Management (TCM) Committee received a $100,000 grant from the National Landcare Program to conduct a major scientific investigation into the causes and remedies of stream instability in the non-tidal reaches of the Nambucca catchment. The project was put to tender and the partnership of the University of Wollongong School of Geosciences and Lyall and Macoun Consulting Engineers was awarded the project. The consultancy project involved a series of technical working papers entitled:

- *Catchment Conditions, Climate and Hydrology;*
- *Sediment Characteristics;*
- *Hydraulics and Sediment Transport;*
- *Riparian Vegetation and Related Issues;*
- *Fluvial Geomorphology, and*
- *River Management and Rehabilitation*

Each of the technical working papers received academic peer review and the findings of the research were included in a separate *Executive Summary and Management Recommendations Report.*

This author carried out all of the necessary fieldwork and report writing for all of the above-mentioned reports, save the *Hydraulics and Sediment Transport* report, as part of a PhD scholarship. Upon completion of all of the technical working papers and recommendations in 1999, further research was undertaken to improve the understanding of the changes in the late Quaternary stratigraphy and chronology in the catchment.

1.4 Aims and Objectives

The instability of the Nambucca River catchment is symptomatic of gravel-bed rivers on the NSW coast. As with almost all other NSW coastal catchments the Nambucca catchment had not received sufficient attention to allow a detailed investigation into the systematic change in fluvial processes from the late Quaternary, through settlement, to the modern day. In doing so, this study provides the most detailed fluvial record for the last 50,000 years of any study of a coastal NSW catchment. The study also aims to demonstrate that an understanding of the cause and effect of land use and climate change since settlement will assist in prescriptive river management for similar catchments along coastal NSW and beyond.

This thesis presents:

- A definitive assessment of the late Quaternary evolution of the Nambucca catchment on the NSW north coast in order to provide a context within which to understand the fluvial impact of European land use changes.

- Evidence for the complex interaction between climate and European land use changes leading to destabilisation and erosion of the stream channels.

- An assessment process to show how a detailed understanding of both Quaternary history and contemporary processes can reveal a great deal about modern channel behaviour and the most suitable approaches for catchment management. This understanding requires a shift from merely identifying and treating the symptoms of degradation towards understanding and working with the fluvial processes at work within the catchment.

- Detailed suggestions based on the above information for the effective rehabilitation and ongoing management of the Nambucca catchment.

1.5 Thesis Outline

Following this introductory chapter, Chapter 2 provides a literature review on the geomorphologic processes of NSW coastal rivers, the principles of river management, and explores the history of gravel extraction and rehabilitation issues in the Nambucca catchment. Chapter 3 examines the climatic, hydrological and land use records from the Nambucca catchment and Chapter 4 is a collation of fluvial information recorded from 36 sites within the Nambucca catchment. Chapter 4 also examines the fluvial processes at work in the Nambucca catchment through examination of fluvial data and a review of historical aerial photographs. An analysis of the influence of riparian vegetation on channel behaviour for both the Nambucca catchment and NSW coastal streams is provided in Chapter 5.

The chronology of late Quaternary terrace and floodplain formations are presented in thermoluminescence and radiocarbon ages in Chapter 6. Chapter 7 reviews the geomorphic history of the catchment from the late Quaternary, through settlement, to the present day. The penultimate chapter, Chapter 8, identifies that processes at work in the catchment and applies the findings of the study (i.e. processes that have altered the catchment through ancient and modern times) for current and future management of the streams in the Nambucca catchment to ensure a sustainable future for this catchment and similar gravel-bed river systems on the NSW mid-north coast. Chapter 9 summarises the findings of this research against the aims outlined above.

2. AN INTRODUCTION TO THE GEOMORPHOLOGY AND MANAGEMENT OF NEW SOUTH WALES COASTAL RIVERS

2.1 Introduction

This chapter presents a review of what is known about the history and geomorphology of NSW coastal valleys. It includes a description of terrace and floodplain formation in NSW coastal valleys and also describes changes in channel morphology associated with climatic variations. It also provides a literature review on the principles of river management and how this has been applied on NSW coastal rivers. It concludes with a description of the history of sediment related river management issues in the Nambucca catchment.

2.2 Geomorphology of New South Wales Coastal Rivers

2.2.1 Background

The character of eastward-flowing coastal rivers in NSW differs greatly from those that flow to the west. The eastward rivers are generally shorter, steeper, confined to narrow valleys in relatively rugged terrain, and transport coarser sediment loads. Annual rainfall values are generally over 1000 mm and in places over 1800 mm resulting, prior to settlement, in heavily forested catchments containing wet sclerophyll and rainforest cover. Frequent coastal storms, steep gradients, confined valleys and unconsolidated sediments result in easterly flowing rivers that can be relatively dynamic. In recent geological time, past sea-level fluctuations have extensively altered erosional and depositional conditions in the downstream reaches of these rivers. Following European arrival forest removal and agricultural development have greatly altered river conditions in these coastal valleys, and these changes are ongoing as the streams continue to adjust to changes of water and sediment inputs and massive alterations in channel boundary conditions.

2.2.2 Landscape Evolution

Our understanding of the origin and evolution of the valleys of Australia's Eastern Highlands has changed rapidly. Less than 160 years ago the spectacular scenery of this belt of eastern high country was believed by Charles Darwin to have been carved by

marine processes resulting from much higher sea levels than today (Nanson and Erskine, 1988). Only with the visit of the American scientist James Dana in 1839 came the major revelation that these canyon-like valleys were carved by the rivers that actually flow within them. However, over the next one hundred years, while the valleys were recognised to be definitely of fluvial origin, it was believed that they must be relatively young, probably formed by rivers with much enhanced discharges and sediment loads during the highly erosive Pleistocene epoch (the past few million years), while large parts of the world were experiencing a series of severe glaciations (see reviews by Nanson and Erskine, 1988; Tooth and Nanson, 1995).

A second major breakthrough in understanding came with the work of Young (1977, 1978, 1983), and Young and McDougall (1982; 1993), based on the dating of basal flows within the valleys. They were able to quantify that these valleys are of great antiquity, resulting from landscape uplift and associated river incision that occurred at least 30 million and possibly as much as 100 million years ago. They showed that far from being the product of a short Pleistocene episode of extreme erosion resulting from an exceptional increase in rainfall, they were eroded under a fairly continuous humid-fluvial regime, not dramatically different from that which prevails today. That is not to say that coastal NSW has not been subjected to Quaternary climate changes and associated variations in run-off and sediment yield. Clearly, as will be shown below, such Quaternary changes have modified within-valley alluvial landforms, such as terraces, floodplains and alluvial stream channels, but such relatively minor changes were not responsible for producing the bedrock river-valleys of the Eastern Highlands of Australia.

Although the Nambucca catchment is located on the more active coastal margin of landscape change in the Eastern Highlands of Australia, and would have been subjected to similar episodes of enhanced gorge-cutting as those experienced by catchments further south, it undoubtedly dates back well into the Tertiary, and it has indeed been evolving very slowly, albeit relatively continuously, over this period. Studies by Young (1983), Bishop et al. (1985), Taylor and Walker (1986), Nott (1992) and Young and McDougall (1993), on the long-term landscape evolution and river valley changes in the uplands of NSW, all point to extremely low rates of tectonism and denudation. In places, the topography of Australia's eastern highlands represents a landscape largely unaltered since the early Tertiary (some 50-60 million years) (Young, 1977, 1978, 1983; Young and

McDougall, 1993). While contrasting greatly with the more active regions of Europe and North America, this stability is typical of large parts of the earth's surface which are of moderate relief and have experienced long periods of tectonic stability (Bishop et al., 1985).

Several comparative studies of continental sediment yields broadly confirm that contemporary Australian values are among the lowest in the world (Walling and Webb, 1983; Olive and Reiger, 1986; Reiger and Olive, 1988). The rivers of Australia's eastern highlands have abundant stream energy at certain times. However, in their *undisturbed* state a pronounced lack of sediment supply means that natural sediment yields must be exceptionally low (Hean and Nanson, 1987). Such long-term channel stability and limited sediment movement has important implications for understanding recent fluvial behaviour in the valleys of coastal NSW where geological stability has been the norm for tens of millions of years. Recent human interference has converted what were naturally exceptionally stable river systems to some of the continent's least stable (Brooks and Brierley, 2000).

2.2.3 Quaternary Environmental Changes

Australia has experienced very little direct glaciation in recent geological time; however, it has been subjected to the major shifts in climate and sea level that accompanied extensive glaciation elsewhere during the Quaternary Period (the past ~2 million years) (Nanson et al., 1993). NSW has a drowned-embayed coastline with a discontinuous and narrow coastal plain that reflects the present high sea-level stand. Small estuaries generally occupy river valleys excavated into bedrock during earlier phases of low sea level (Roy et al., 1980), and these estuaries often contain a sedimentary record of coastal and fluvial activity (McMinn, 1992).

Sedimentation of NSW estuaries during the Quaternary has been dominated by the effect of eustatic sea-level changes (McMinn, 1992). However, the sequence of Quaternary deposition in most valleys of coastal southeastern Australia above the tidal limit is poorly understood. During periods of low sea level (glacial maxima), the estuaries were displaced, their present positions becoming areas of erosion, with sediment being transported to estuaries relocated on to the continental shelf. During periods of high sea level (glacial minima), the coastal valleys were drowned and new estuaries formed up-

river at coastlines near to the present. The terrestrial record of fluvial geomorphic change along the coast of NSW during the Quaternary is very dependent on the record preserved in river estuaries, terraces and floodplains.

Nanson and Erskine (1988) stated that there is no evidence to indicate that Pleistocene climatic fluctuations produced exceptional fluvial erosion beyond areas directly affected by glacial or periglacial processes. Clearly, there were episodes of greater and lesser erosion, but the Tertiary-age Londonderry Terrace on the Hawkesbury-Nepean River was forwarded as an example of Pleistocene terraces having Tertiary or pre-glacial counterparts. They continued this theme stating (p. 204):

> "Coastal NSW is an environment where most rivers have, since the early-to mid-Tertiary, operated uninterrupted by the direct effects of glaciation or by prolonged periods of aridity. Unlike many rivers studied elsewhere, these have no large stores of sediment derived from Quaternary glaciation or tectonism. Long term denudation rates are very low (Young, 1983) as are contemporary sediment transport rates (Olive and Reiger, 1988). These rivers must be close to being in a state of truly long term "adjustment" with the landscapes they have created. However, this does not necessarily mean they are under conditions of steady state or dynamic equilibrium. It remains to be established just what the contemporary pattern of fluvial erosion and deposition is in landscapes of such antiquity, relative stability and low denudation."

Broadly speaking, glacial fluctuations elsewhere in the world presented coastal NSW with conditions that probably fluctuated between relatively wetter interglacial and relatively drier glacial periods (Nanson et al., 1992). Coupled with this were fluctuations in sea level between glacials (low) and interglacials (high) that must have greatly affected the lower reaches of the coastal rivers.

2.2.4 River Terraces

Over periods of decades or centuries, only a small fraction of the total alluvium in a river valley is transported by the river; the bulk is stored in floodplains or alluvial terraces (Nanson and Croke, 1992). River terraces are an integral part of most fluvial landscapes and they occur widely in the Nambucca catchment. For many years the existence and

formation of terraces have been the subject of considerable research, for they represent discrete landforms and a relative chronology (higher terraces being older than lower terraces) to which other events (geomorphologic, marine, geological or hydrological) can sometimes be related (Dawson and Gardiner, 1987). It has been tempting to link the relative chronologies of Quaternary terraces to independently developed chronologies for major environmental changes (Veldkamp, 1991), including palaeoclimatic, eustatic (sea level) and tectonic (geological uplift) change.

Leopold et al. (1964) give a straightforward definition of a river terrace as "an abandoned floodplain", a situation arising from the river incising below its previous floodplain. This emphasises the fact that the terrace is no longer associated with the contemporary flow regime. Their work popularised established theories that river terraces are the result of tectonic and climatic factors, and they reiterated that tectonic forces, such as folding, tilting, faulting or warping, affect the gradient of a river system and, therefore, the delivery of sediment. Climate change, although an indirect factor, leads to differences in the hydrologic regime, thereby affecting the water and sedimentary delivery to the system (Leopold et al., 1964).

Bull (1990) describes river terraces as being of three generic types: tectonic; climatic; and complex response. However, a fourth type that is base-level determined, must commonly occur in proximity to fluctuating sea levels (Nanson et al., 2003). River valleys along the east coast of NSW exhibit similar evidence of Quaternary age terrace development, and only in their lowermost reaches have they been influenced by Quaternary eustatic changes (Nott et al., 2002).

In looking at terrace types on a NSW coastal river Warner (1972) showed four alternative ways in which a floodplain can be abandoned (Figure 2.1). Starting with a normal floodplain (Figure 2.1a), a fall in discharge may cause a new floodplain to be inset below the level of the old floodplain (Figure 2.1b). In this instance, the bedrock valley floor is not incised and both the terrace and floodplain share the same bedrock trench. If the stream has higher flood levels than previously experienced and aggrades, the original floodplain may be 'overlapped' or buried (Figure 2.1c); this, Warner reasoned, can also result from a positive movement in base level. In a narrow valley with little potential for lateral movement, formation of a new floodplain at a lower level may, Warner proposed,

be accompanied by renewed erosion in the floor of the bedrock trench. Erosion of this type may result from tectonically induced uplift, a fall in base level, continued downcutting in the upper parts of a valley, or from climate change. This will result in incision of the bedrock valley floor (2.1d) and Warner suggests that numerous floodplains of this type on the NSW north coast are the result of climate change.

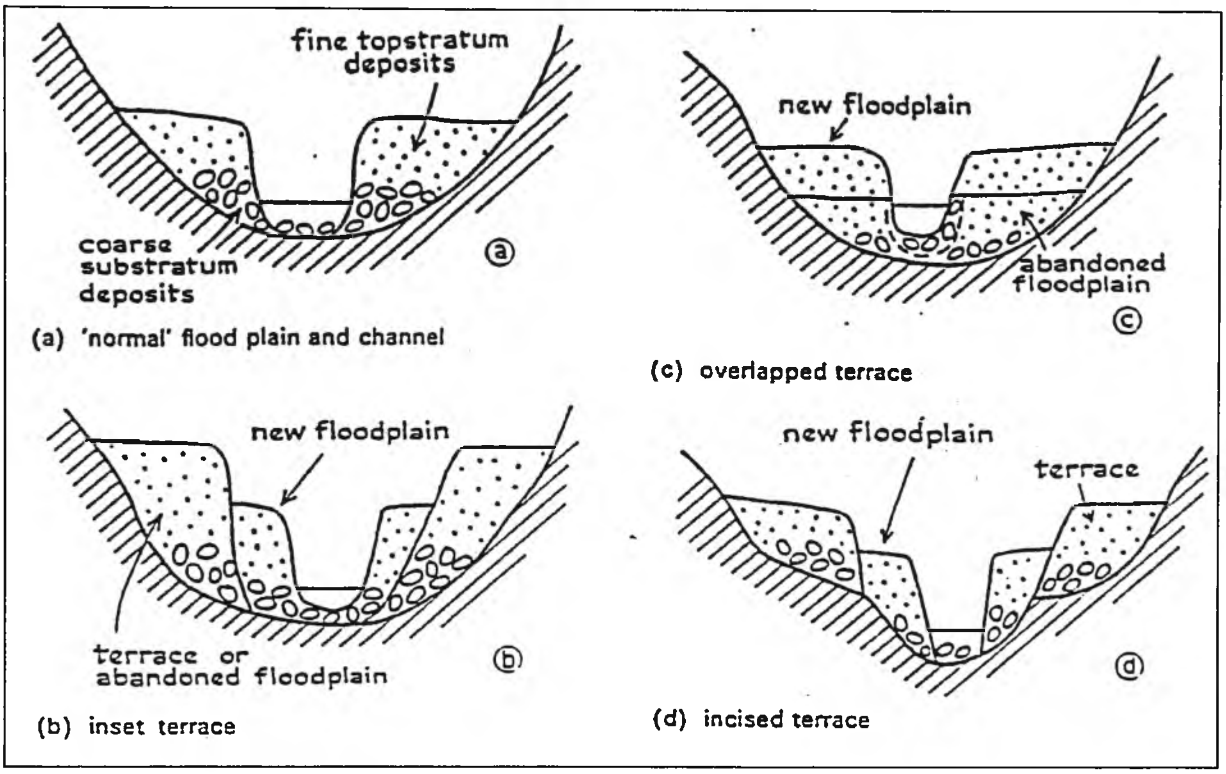


***Figure 2.1: Types of river terrace, based on type of floodplain abandonment** (Warner, 1972).*

2.2.4.1 <u>Thresholds and the Formation of River Terraces.</u>

While early studies dealing with the origin of river terraces focused exclusively on external (extrinsic) factors such tectonics and climate change as explanations, the importance of internal (intrinsic) factors, although mentioned by Challinor in the 1930's, did not become fully acknowledged until work by Schumm (1973; 1977). Schumm (1973) developed the ideas of Leopold (1951) and showed that fluvial landforms can be affected by adjustments inherent in progressive erosion. He introduced the terms 'geomorphic thresholds' and 'complex response drainage systems'. These concepts proposed that

components of even long-lived geomorphic systems do not have to be in state of continuous equilibrium.

In experimental work Schumm showed how rejuvenation and a change in base level can form terraces. These changes were a result of local or intrinsic factors, and not from forcing outside the system. When erosional thresholds are exceeded in an individual catchment, the resulting changes may not occur in neighbouring regions or even in neighbouring catchments. Incision, or rejuvenation, can begin at the mouth of a trunk channel and moves upstream, rejuvenating tributaries as it moved past them and causing subsequent aggradation of the trunk channel downstream. As the tributaries adjust to the new base level, their sediment contributions decrease and a new phase of incision commonly occurs in the trunk stream. From this experiment, Schumm showed that within a complex natural system, one event (perhaps an exceptional storm) can trigger a complex reaction as the system's components respond progressively to change. An infrequent event performing little of the total work within a drainage system can be the catalyst that causes a geomorphic threshold to be crossed, thereby triggering a complex sequence of land-modifying events (Schumm, 1973).

Young and Nanson (1981) and Young et al. (1986) argued that, at least for the past 16 ka or so, river terrace deposition in coastal New South Wales does not always appear to exhibit clearly identifiable patterns of regional climate change. This, they argued, was firstly because the record at that time was based on a radiocarbon chronology biased by the progressive loss of older carbon from the system, and secondly, because intrinsic changes and associated terrace formation can confuse any neat chronological clustering of alluvial deposition. Modern floodplains in the Illawarra region offer insights into how Holocene terraces may have formed, with erosional trenching due to urban expansion in places having turned urban floodplains into terraces (Nanson and Young, 1981). They later reasoned (Young and Nanson, 1981) that terrace formation in the Illawarra region could have arisen naturally from incision as a result of an increase in stream power due to a decrease in channel sinuosity that is not necessarily related to external changes in the environment. Their work found that the deposition of fine cohesive materials in stream banks, in combination with low stream power, has stopped channel migration and resulted in the long term aggradation of downstream floodplains, with associated channel contraction. The effect is a downstream decrease in the size of many Illawarra stream

channels. Where a channel bend is cut off, or where the channel otherwise shifts off its gravel base and into the fine-grained floodplain alluvium deposited by low-energy overbank deposition, sudden incision and channel expansion could result in the periodic abandonment of floodplains to form terraces. Although terraces in the region could arise from a change in sediment load or climate, threshold conditions mean that the magnitude of such external changes need only be relatively slight or short term compared to what has originally been thought of as necessary to account for terrace formation (Young and Nanson, 1982).

A number of recent studies have shown both in NSW (Prosser, 1991; Prosser et al., 1994 Fryirs and Brierley, 1998) and overseas (Patton and Schumm, 1975; Schumm, 1980; Graf, 1983; Bull, 1990) that cut and fill floodplains and associated terraces can be formed in an asynchronous fashion throughout a region in response to a combination of intrinsic and extrinsic factors. Walker (1962) attributes the occurrence of terraces on the south coast of NSW to the glacial cycles and sea level change. However, following the alternative proposal from Young and Nanson (1982), Walker (1984) agreed that Holocene episodes of stream aggradation and incision in the Illawarra region may have also been controlled by local intrinsic factors.

For the period prior to the Holocene, the fact that NSW coastal streams have terraces with diagnostic features in common, such as sediment texture, weathering and soil development, suggests that extrinsic factors have controlled the development these more widely distributed and uniform examples (Walker, 1984). Nevertheless, it is becoming accepted that certain terraces are better explained as the result of relatively minor changes in the magnitude and frequency of storm events, or to the achievement of threshold conditions that trigger a sudden and dramatic change in a landform system, and not necessarily to major changes in climate (Leopold, 1951; Schumm, 1973). The difficulty remains in detecting which terraces are indicators of palaeoclimate or eustatic changes, and which are the product of changing threshold conditions, or indeed, which alluvial features are terraces and which are contemporary floodplains (Nanson, 1986). Generally speaking, if a terrace is topographically widespread and has fairly uniform characteristics from basin to basin, then it is probably due to some widespread environmental change rather than to locally independent threshold responses.

2.2.5 Floodplains

Floodplains are defined geomorphically as: "*the largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks, and built of sediment transported by the present flow regime*", and their evolution is dependent upon the product of stream power and sediment characteristics (Nanson and Croke, 1992 p. 460). While they can be classified into a variety of types, they are effectively a landform continuum ranging from those formed in high energy mountain valleys to those formed on lowland plains. They form as a result of numerous processes but two of these are usually paramount either separately or jointly along most single-thread channels; lateral point-bar accretion and overbank vertical-accretion (Figures 2.2 and 2.3). Lateral point-bar accretion is the product of the progressive deposition of point bars on to the convex bank of a meander bend as the result of cut bank erosion, helical flow and steep shear-stress gradients within the bend. Progressive erosion of the cut bank and accretion of the opposite point bar causes channel migration with the new point bar usually being capped with overbank sediment (Wolman and Leopold, 1957). Overbank vertical-accretion results from the overbank deposition of sediment during floods. It has been shown to be the dominant process along certain single-thread low-gradient NSW coastal channels where there is insufficient stream power to permit channel migration (Nanson and Young, 1981), but clearly these processes operate concurrently in many situations.

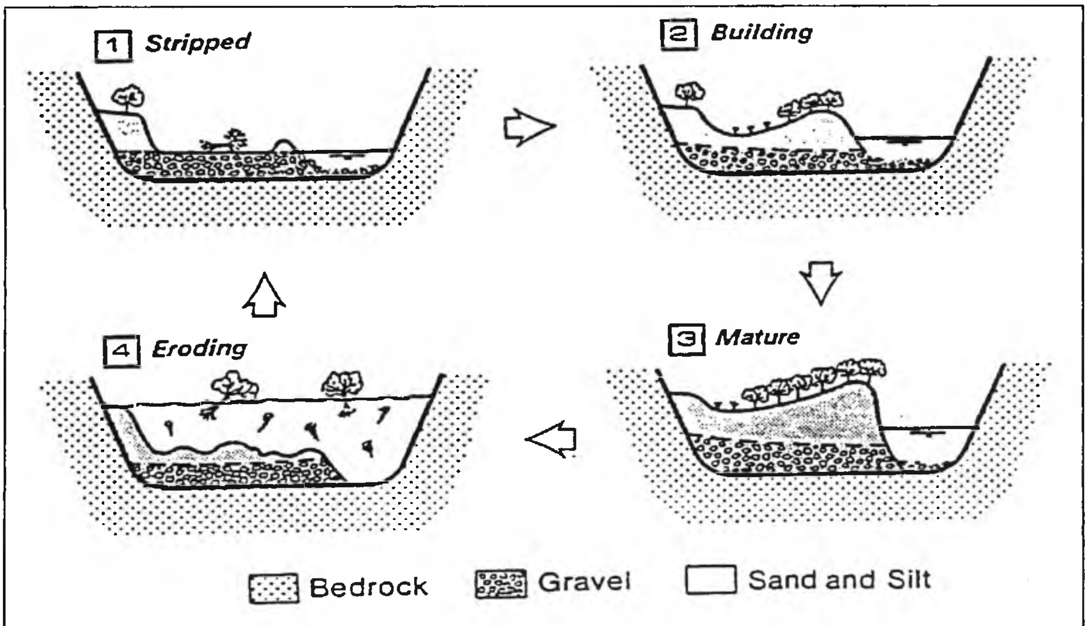


Figure 2.2: The cycle of catastrophic stripping and floodplain rebuilding
(Nanson, 1986)

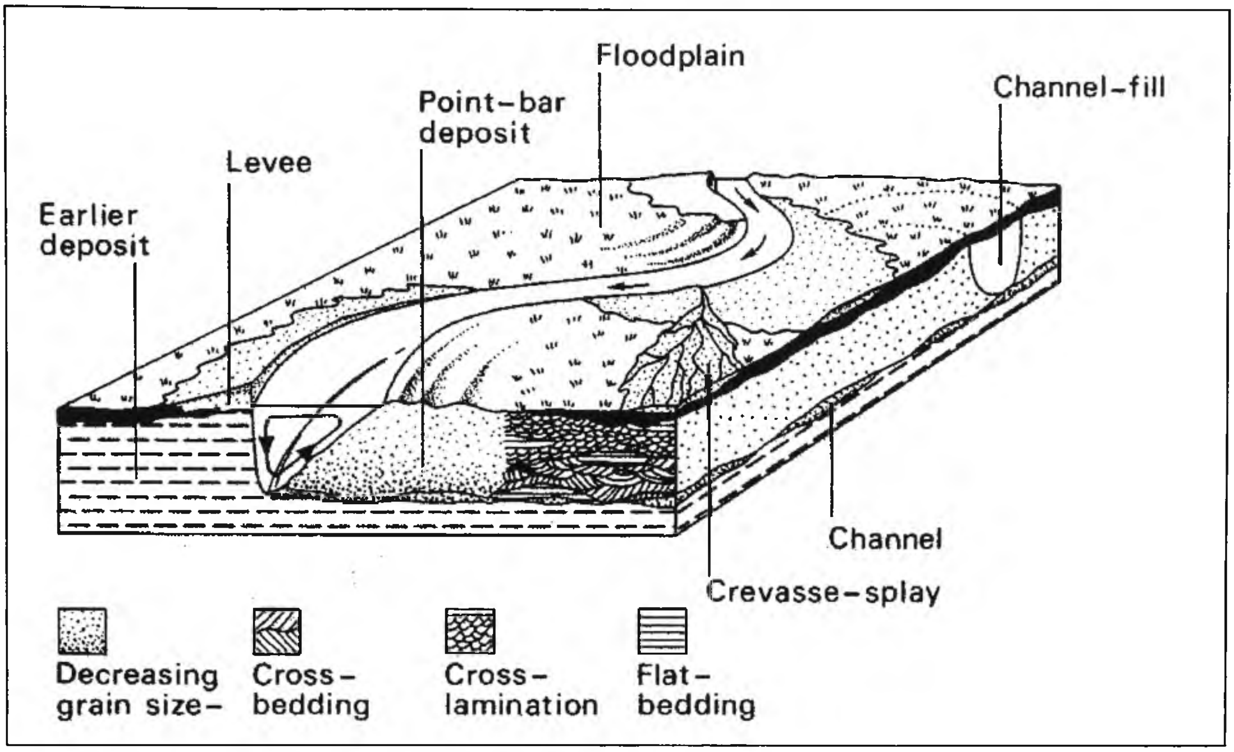
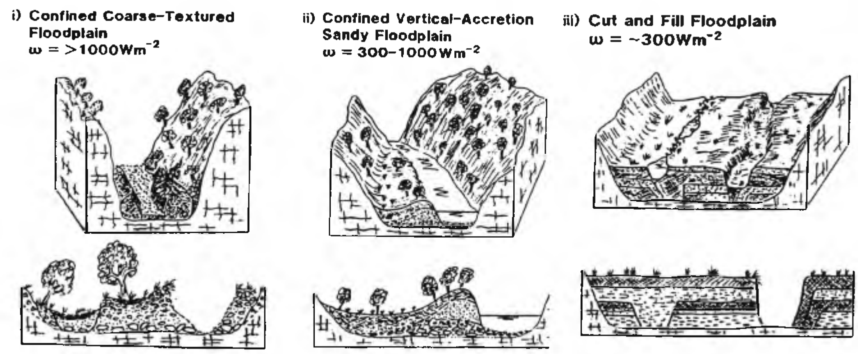


***Figure 2.3: Floodplain processes from lateral accretion and overbank deposits** (Summerfield, 1993)*

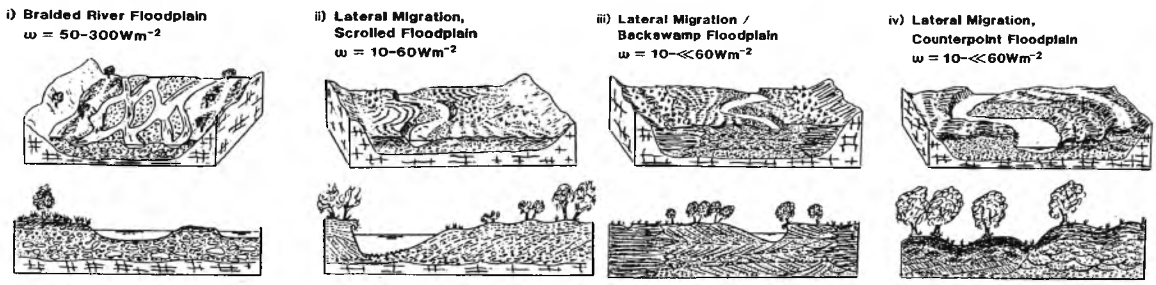
Based primarily on stream power and sediment character, Nanson and Croke (1992) divided floodplains into three primary classes on the basis of stream energy and bankfull flow and sediment cohesiveness (Figure 2.4), and Ferguson and Brierley (1997) have confirmed this classification appears to work well on the coastal Tuross River of NSW. Because of the importance of floodplain evolution and stratigraphy for interpreting past environments in the Nambucca catchment, those parts of Nanson and Croke's floodplain classification deemed relevant to this study are reviewed here.

CLASS A
High Energy,
Non-Cohesive



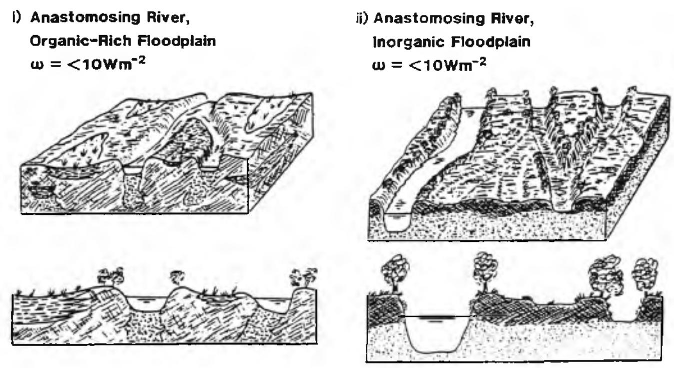
High energy non-cohesive floodplains. (i) Confined coarse-textured floodplain (after Stewart and Lamarche, 1967 and Baker, 1977). (ii) Confined vertical-accretion sandy floodplain (after Nanson, 1986). (iii) Cut and fill floodplain (after Prosser, 1988).

CLASS B
Medium Energy, Non-Cohesive



Medium-energy, non-cohesive floodplains. (i) Braided river floodplain showing gravel bars and fine overbank deposition on the floodplain. (ii) Lateral-migration scrolled floodplain (after Nanson, 1980). (iii) Lateral-migration/backswamp floodplain (after Blake and Ollier, 1971 and Kesel et al. 1974). Lateral migration results in a central deposit of laterally accreted alluvium flanked by organic and fine-grained clastic overbank accretion. (iv) Lateral-migration counterpoint floodplain (after Nanson and Page, 1983). The counterpoint floodplain is forming against the concave bank of the nearest bend at a slightly lower elevation with its surface deposits finer grained and higher in organics than those on the rest of the floodplain. Flow is towards the observer.

CLASS C
Low Energy, Cohesive



Low-energy, cohesive floodplains. (i) Anastomosing river, organic-rich floodplains (after Smith and Smith, 1980). Vertical accretion is laying down overbank muds and lacustrine deposits around near-vertical stringers of sand or gravel beneath each channel. Swamps and lakes can result in widespread paludization. (ii) Anastomosing river, inorganic floodplains (after Nanson et al., 1986, 1988 and Rust and Nanson, 1986). To the right of the diagram, anastomosing channels are incised into cohesive floodplain mud with coexistent shallow braid-channels over the floodplain surface. To the left of the diagram, a waterhole has scoured beneath the mud into a sand sheet deposited during an earlier flow regime (Nanson et al., 1988).

Figure 2.4: Diagrammatic representation of the Nanson and Croke (1992) system of floodplain classification.

Class A. ***High energy non-cohesive floodplains*** (specific stream power at bankfull: usually > 300 watts per square metre - W/m^2). These are disequilibrium landforms that are eroded, either completely or partially, as a result of infrequent extreme events. In some cases floodplains that are close to some threshold condition may erode as a result of a series of moderate events. Stream power is typically high because of their location within steep upland areas, and bank erodibility is primarily a function of the linear relationship between the size of sediment entrained and stream power, although vegetation can modify this. Despite their high energy nature, these channels are usually prevented from migrating laterally by very coarse alluvium or bedrock, and their floodplains are dominated by relatively uncohesive vertical-accretion deposits. Because of their confined nature and relatively steep gradients, these floodplains are restricted to the upper reaches of NSW coastal rivers. This class is divided into four orders, two of which appear to be relevant to the Nambucca (Nanson and Croke, 1992):

Order A1, *confined course-textured floodplains*, occur in narrow bedrock valleys and are formed somewhat chaotically of poorly sorted gravel and boulders deposited by very large floods. They usually have an uneven bouldery surface, commonly characterised by chute channels, abandoned channels, levees, partial floodplain stripping, splays and scour holes, partially caped with a variable but thin deposit of overbank fines. Unit stream power in the adjacent channel at bankfull is usually in the order of 1000 W/m^2 or greater. They occur in the forested headwater streams of the Nambucca catchment but are not present in the study reaches. The gross alluvial topography is characterised by disjunct flanking terraces, remnants of older floodplains and contemporary floodplains. Because they are normally forested and their stratigraphy is reinforced with boulders, they probably are eroded severely under rare conditions, possibly when an intense fire destroys floodplain vegetation and this is followed almost immediately by an extreme flood event that erodes the floodplain.

Order A2, *confined, vertical-accretion sandy floodplains*, have a well defined laterally stable channel, and in their mature form they have very distinctive levees and a well defined backchannel that in combination can produce a floodplain surface of considerable local relief. They form by the vertical accretion of silty sand, sometimes over a gravel base, along channels with bankfull unit stream powers of 300-1000 W/m^2. The

considerable depth of silty-sandy overbank deposition and relatively smooth well-rounded overbank topography clearly distinguishes them from Order 1A. Because of their high-energy location, a well-developed grass sward or other form of dense vegetation appears essential for maintaining their stability. This type occurs very commonly in the upper and middle confined reaches of NSW rivers but they are more powerful rivers than the middle and lower reaches the Nambucca streams prior to European settlement (i.e. before channel enlargement). Nevertheless, some of the upstream floodplains within the study area appear to be of this type.

Class B. ***Medium energy non-cohesive floodplains*** (specific stream power at bankfull: 10-300 W/m^2). These floodplains are reworked by their actively braiding or meandering rivers and are commonly in dynamic equilibrium with the annual or decadal flow regime of the channel.

Order B3, *Meandering river, lateral-migration floodplains*, are the most common type of floodplain to have been described in the scientific literature and occur along rivers where specific stream power varies between about 10-60 W/m^2. They form as a result erosion of a cut bank in a river bend, and lateral and vertical growth of the opposite point bar and associated overbank deposits. This type appears to be widely represented in the palaeo-floodplain deposits of the middle and lower reaches of the Nambucca catchment, extending into estuarine reaches. Where gravels are present there can often be a well-defined point-bar platform on which within-channel fines and overbank deposits accrete.

Class C. ***Low energy cohesive floodplains*** (specific power at bankfull: <10 W/m^2). These are usually associated with laterally stable single-thread or anastomosing channels. Low stream power is primarily a function of their small channel size and/or their very low slope, and as with Class B above, floodwaters readily spill overbank, dissipating erosional energy. Bank resistance is high due to their fine-grained cohesive composition, which inhibits lateral migration. These floodplains are formed predominantly by vertical accretion of fine-grained deposits and by infrequent channel avulsion.

Order C1, *Laterally stable single-channel floodplains*, appear to have been the dominant type in the Nambucca catchment immediately prior to European settlement. They can form spatially due to a decline in channel capacity, a reduction in available stream power,

an increase in fine cohesive sediment deposition (Nanson and Young, 1981) or the dominance of channel bank vegetation.

2.2.5.1 The Bellinger Catchment Floodplains.

Warner (1992) described the floodplains in the Bellinger catchment flanking the northern boundary of the Nambucca. He shows that floodplain stratigraphy and morphology change downstream as gradient declines and the size of the valley trough progressively increases. Because of the proximity of the Bellinger to the Nambucca, Warner's observations are also reviewed in detail. He states that:

> *The Bellinger and its southern neighbours, the Kalang and the Nambucca Rivers, are different to many other coastal rivers in that: they are shorter with smaller catchments, they generally flow easterly towards the coast (many others have considerable north and south flowing components) and they are cut solely in lower Palaeozoic materials.* (Warner, 1992, p.453)

In the upper and middle catchment he recognises narrow valley troughs with channels that take up much of the valley width, leaving discontinuous segments of *Type 1* floodplain, probably frequently reworked by extreme events (Figure 2.5). These appear to be essentially the *confined, coarse-textured floodplains* of Nanson and Croke (1992), characterised by frequently reworked alluvium. Warner distinguishes between valley reaches where the channel has further incised into the bedrock valley floor, and those where it has not. However, this distinction is not readily apparent in sections exposed along the Nambucca's streams. His Type 1 occurs as discontinuous higher and lower floodplains. Perched and dissected terrace bases indicate that downcutting has post-dated prior-floodplain abandonment. The narrow valley represents a poor alluvial store and most of the deposits are probably fairly recent in age. Channel slopes here are steep, and most of the finer sediment is carried and deposited in the wider, lower-energy environments downstream. Boulders dominate the surviving floodplains. This type extends for >50 km down-valley, more than half the length of the Bellinger river and much further downstream than is evident for confined coarse-textured floodplains (A1) in the Nambucca catchment.

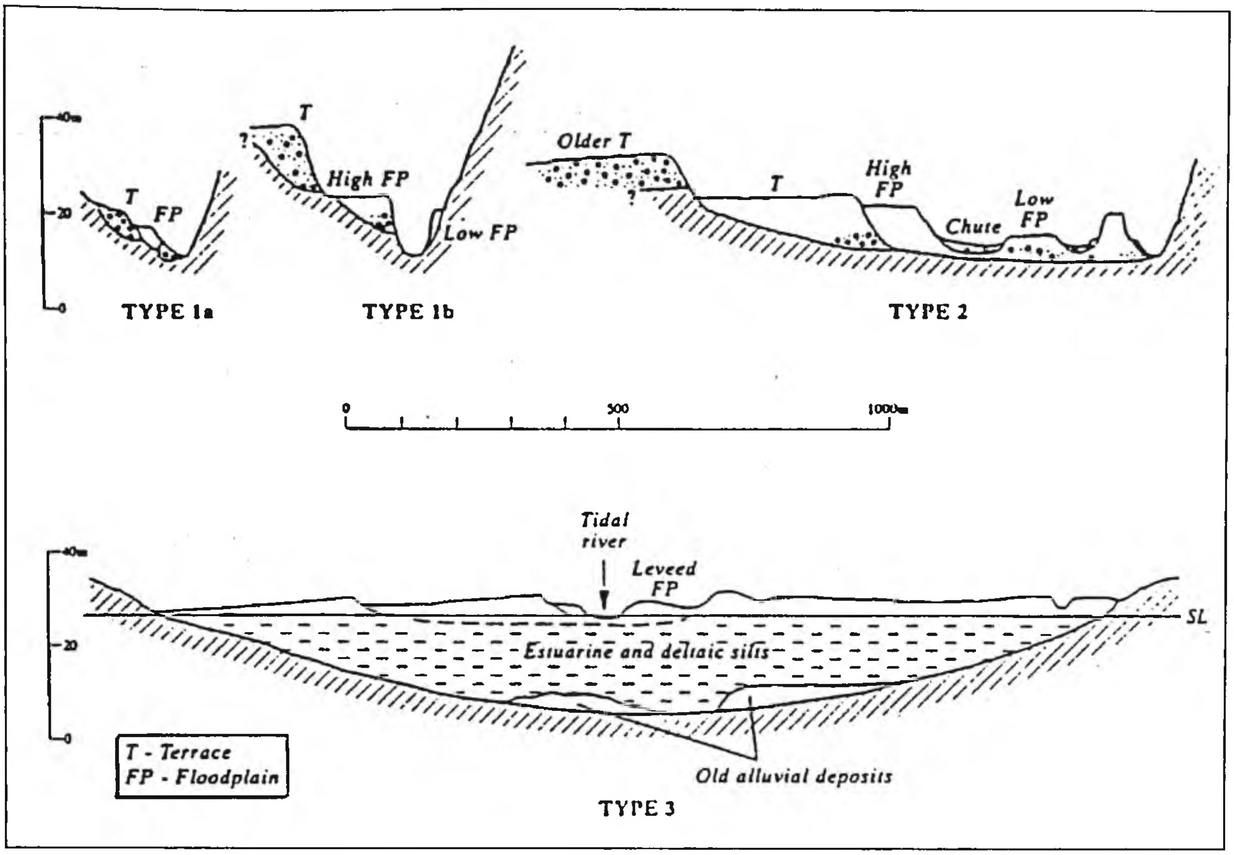


Figure 2.5: Warner's (1992) Valley floor trough types in the Bellinger catchment

Warner's *Type 2,* floodplains (Figure 2.5) occur in the lower middle and middle reach over a short 10-12 km of length of valley immediately upstream of the present tidal limit, and are characterised by flanking inset Pleistocene terraces, wider floodplains formed by laterally reworking of older Quaternary deposits, meandering channels and chute cut-offs across meander necks (rather than parallel to the main channel as in Type 1). This type appears similar to Nanson and Croke's (1992) Suborder B3 *Meandering river, lateral migration floodplains* but with abundant chute channels present. Here the valley is relatively wide and contains lag gravels of Pleistocene terraces as well as more recent alluvia. Non-incised gravel floor deposits may well be reworked deposits from former steeper, low sea level related channels and their Pleistocene floodplains. This is essentially a condition where the modern floodplain is inset within a high floodplain and a couple of terraces. As gradients are less than upstream, energy levels are lower, and flooding conditions are more extensive and energy dispersive with less evidence of floodplain erosion. As stated above, this type of floodplain (B3) appears to be the dominant type in the palaeo-floodplain stratigraphic record of the Nambucca catchment.

Warner's (1992) Type 3 floodplain occurs in the tidal reach of the river, and consist of a thin capping of fluvial sediment overlaying estuarine deposits from periods of higher sea level. With low gradients and low energy, floods spill out onto the floodplain to cover levee toes and swamps. This type is not present in the Nambucca study area, but does occur downstream of the tidal limit.

Dating Warner's three valley floodplain types reveals that the upper floodplains are the youngest, with the lower, or tidal region being the oldest . The downstream progression in age is a function of high energy and valley confinement in the upper reaches and sea level control and low energy in the tidal reaches.

2.2.6 In-channel Benches

It is not uncommon for Australian rivers to exhibit narrow low 'floodplains' adjacent to the channel and below the level of the main floodplain. These are sometimes referred to as inset floodplains or lower floodplains, but Woodyer (1969) and Taylor and Woodyer (1978) described them in some detail and called then alluvial benches. These appear to be an effective means of adjusting channel geometry and sediment storage in the short term in some rivers (Erskine and Livingstone, 1999).

2.2.7 Flow-regime Variability and Geomorphic Response

Cornish (1977) showed that there was a 21% increase in annual rainfall in New South Wales from the period 1888-1945 to the period 1946-1975. Systematic variations in flood dominance through time have been detected on NSW rivers near Sydney and interpreted as evidence of secular climate change (Pickup, 1974, 1976; Erskine, 1986; Warner, 1987a; Erskine and Warner, 1988). From an analysis of 200 years of flow records on the Hawkesbury River at Windsor, Warner (1987a) recognised three periods of flood-dominated regime (FDRs), 1799-1820, 1857-1900 and 1948 to the present, and two periods of drought-dominated regime (FDRs), 1821-1856 and 1901-1947. The changes were substantial with the mean annual flood ($Q_{2.33}$) for the DDR only about 350 m^3s^{-1} compared to the present FDR with about 800 m^3s^{-1}. Erskine and Warner (1988) argued that this pattern is common along the NSW coast, particularly for those rivers north of Sydney. Nanson and Erskine (1988) proposed that, on the basis of this evidence, certain

rivers should change from narrow deep channels to wide shallow ones in response to factors associated with FDRs and DDRs driven by secular climate change.

The 20-50 year FDR-DDR episodes could mean that NSW coastal river channels never properly adjust to regime conditions; such channels and floodplains may periodically undergo major changes simply as a result of relatively short-term changes in climate. Indeed, this rationale is now being used to explain major erosional changes and guide management policies on the Cann River in East Gippsland (Erskine, 1992). However, Kirkup et al. (1998) have undertaken a detailed examination of the rainfall record attributed to the FDR-DDR theory and have found little support for the concept that secular climate change is driving channel change on the coastal rivers of eastern Australia. They argue that inter-annual seasonal variations do not show marked differences in rainfall as supposed for FDR and DDR phases. They maintain that there is no climatological evidence for a 30-50 year cycle in rainfall pattern and no known underlying mechanism that could drive such a supposed cycle. Their evidence suggests that other conditions in the catchment, such as changes in land use, are more important for predicting channel change than are any recognisable cycles in rainfall and flooding. Critical controls of channel change are sediment availability, bed stability and the condition of riparian vegetation. They argue that focussing attention of supposed climate cycles could direct scientific attention away from more primary causes.

Regardless of the evidence for FDR and DDR episodes, it is generally appreciated that there has been a significant shift in coastal NSW from a generally drier less flood prone regime in the first half of the twentieth century, to a wetter more flood prone period after 1948 (Pittock, 1975; Cornish, 1977; Erskine and Bell, 1982; Erskine, 1986; Nicholls and Lavery, 1992). However, whether this is part of a widespread, relatively consistent cyclic pattern measured in decades on the east coast of NSW and Victoria is not yet resolved, nor has the impact of this change on channel and floodplain morphology and stability been fully evaluated.

From residual mass curves for various long-term stations including Macksville and Bowraville, (see Chapter 3 on hydrology and land use) a number of distinctly wet periods in the Nambucca catchment have been identified. These were 1890-1895, 1950-1965, 1973-1978 and 1989-1992. Of these the periods 1890-1895 and 1950-1965 show the

most pronounced above-average values. Unfortunately the lack of long-term records has prevented a similar analysis for stream flow data. While residual mass curves for rainfall are not necessarily an indication of increased flood magnitudes, the 1890-1895 and 1950-1965 periods do coincide approximately with two episodes of greater than usual flooding at Bowraville recorded by the NSW Dept of Public Works (1980).

Unrelated to the FDR-DDR controversy, Nanson (1986) has recognised that floodplain formation and erosion is highly episodic with periods of erosion that are probably linked to extreme flood events, or to clusters of large although not necessarily extreme floods. Such events can trigger threshold conditions and rework huge volumes of sediment by way of bank erosion or floodplain stripping. Channels most likely to exhibit this type of change are those that are in narrow valleys and do not laterally migrate, therefore do not progressively adjust their geometry to changing flow conditions. Such a channel usually builds its floodplain by vertical accretion and therefore, as years go by, it retains more and more flood discharge, concentrating erosional energy within its banks. Eventually, such channels exceed the erosional threshold of their boundary. Most active floodplain stripping and channel widening occurs along high energy channels with sandy floodplains that can be eroded catastrophically by large floods or clusters of floods. Such floodplains are subsequently reconstructed predominantly by overbank deposition (Figure 2.2) (Nanson, 1986).

Spatial climatic variability and the combination of extrinsic and intrinsic thresholds probably explains, in part, why it has been difficult to clearly identify accretionary or erosional phases over the past 5000 years recognisable from the pooled data of NSW coastal rivers (Young et al., 1986). While the absence of a clear widespread and uniform pattern lends support to the notion of Schumm (1973; 1977) that localised factors are of considerable importance in controlling the adjustment of fluvial systems on the NSW coast, the recent compilation of floodplain and terrace chronologies by Nanson et. al. (2003) does identify strong climatic overprinting.

2.2.8 Catchment Characterisation

Brierley and Fryirs (2000) characterise different channel types within NSW coastal catchments and prescribe different recovery mechanisms to suit the fluvial processes operating within each different *river style.* Geomorphically-derived river styles provide an

integrative framework for examining the interactions of biophysical processes in rivers throughout a drainage basin. Nine styles of river character and behaviour were identified in the Bega catchment, on the south coast of NSW. Headwater streams above the escarpment drain into gorges in the escarpment zone. In different sub-catchments at the base of the escarpment, there are three different river styles, namely cut-and-fill, vertically accreted floodplains, and fans. Downstream of these river styles, in the rounded foothills of the catchment, throughput and transfer river styles convey sediments to the lowland plain. In one mid-catchment setting, a floodout traps sediment. Finally, along the lowland plain of Bega River, there is a floodplain accumulation river style. Downstream patterns of river styles in differing sub-catchment of the Bega River basin are differentiated into three types, reflecting river adjustments to valley width, slope and responses to human disturbance (Brierley et al., 2001; 2002).

Analysis of the character and condition of each river style in the Bega catchment, and their downstream patterns, were used to provide a biophysical basis to prioritise river management strategies. These reach-scale strategies were prioritised within an integrative catchment framework. Conserving near-intact sections of the catchment was identified as the first priority. Secondly, the parts of the catchment with natural recovery potential are to be targeted and, finally, rehabilitation priorities are to be considered for highly degraded reaches. At these sites, erosion and sedimentation problems may reflect irreversible changes to river structure (Fryirs, 1999).

2.2.9 Aboriginal and Post-Settlement Geomorphic Change

Hughes and Sullivan (1981) proposed that prior to European settlement, aboriginal burning has substantially increased fluvial sedimentation. More extreme views have suggested that the arrival of Aborigines could have completely altered the vegetation and climate of much of the continent since their arrival about 60,000-50,000 years ago (Flannery, 1994; Miller and Magee, 1996). If this is true then it would surely have lead to substantial geomorphic changes in the Nambucca catchment. However, at this stage there is no evidence to support this contention.

While there is no evidence to support the argument that Aborigines *greatly* altered the geomorphic landscape, there is certainly a growing appreciation of the extent to which

Europeans have caused dramatic change. Eyles (1977 a and b) has presented evidence to show that discontinuous chains of ponds along streams on the Southern Tablelands near Canberra were converted to eroded gullies as a result of increased run-off due to forest clearance and the introduction of stock that trample the soil and reduce infiltration. In a study of Lake Illawarra near Wollongong, Young (1976) estimated that over the period of European settlement in the lake catchment, sedimentation rates where increased by six times. A lack of gullied hillslopes, but greatly enlarged channels, suggests much of this erosion attributed to European settlement in NSW has resulted largely from dramatic channel erosion rather than hillslope wash (Wasson, 1998). Recently, Fryirs and Brierley (1998) and Brierley and Fryirs (1998) have given evidence that suggests that major channel incision and river metamorphosis since 1900 on a small tributary of the Bega River on the south coast of NSW has been initiated by European disturbance, and Brooks and Brierley (1997) found that prior to European settlement in the 1850's, the Bega River on the south coast of NSW had a relatively deep channel lined with trees and by 1926 the channel had widened extensively (up to 3.5 times) and greatly shallowed. Conversely, Haworth et al. (1999) presented evidence from a small lagoon on the New England Tablelands, a site only 100 km northwest of the Nambucca catchment, that European settlement and land clearance transformed the landscape with the introduction of hillslope erosion and downstream sedimentation.

It is noteworthy that all but one of the above studies identified channel erosion rather than overall hillslope erosion as the source for post-settlement sedimentation. There seems little doubt that in many NSW catchments, European deforestation of catchments, and in particular the clearance of vegetation from stream banks, has caused channel incision and bank erosion that has led to serious channel deterioration and downstream sedimentation.

Clearly controversy remains as to the geomorphic impact of secular climate change compared to European settlement on the NSW landscape. However, there is a growing appreciation that European land clearance and the development of agriculture over the past 150 years, in addition to short-term climatic influences, must be considered as causes of channel and floodplain instability in the previously well-forested eastern catchments of NSW and Victoria.

2.3 Principles of River Management

River management is often categorized through the selection of engineering or conservation/rehabilitation techniques. Stream size, land use practices, and the extent of channel and catchment degradation, are all factors that determine the scale and type of river management practices to be adopted. Broadly, the rationale adopted for river management and rehabilitation can lead to one of two outcomes; altering the river environment to best suit land use practices or, altering land use practices to best suit the river environment.

Some forms of river management and rehabilitation fit into both categories and are not mutually exclusive. For example, revegetation of the toe of a bank can halt bank erosion and allow agricultural practices to proceed with fewer disturbances. Accordingly by excluding stock from the bank, the river environment can be rehabilitated without the added disturbance of anthropogenic disturbance. Altering the river environment can also be broadly separated into two approaches - river engineering, and river conservation and rehabilitation:

River engineering includes a number of methods associated with direct structural interference with the waterway to alter flooding, erosion, sedimentation or water use. These methods include:

- flood mitigation works (eg. levee construction, desnagging)
- urban channel reconstruction (eg. enlarging, concreting)
- river training for erosion control (eg. groynes)
- dam and weir construction
- bed alteration and sediment control (eg. dredging)
- channelisation (eg. re-alignment)
- sand and gravel extraction

River conservation or rehabilitation does not involve direct structural change to a river. The methods here are targeted at minimising negative inputs through land use control

and by encouraging or accelerating natural recovery methods. Conservation and rehabilitation techniques include:

- water quality control
- habitat diversity maintenance (eg. pools and riffles)
- vegetation management (eg. tree planting, weed control)
- 'soft' engineering control of moderate bed and bank erosion
- land use controls (eg. cattle access)

The rehabilitation of degraded rivers has recently become of increasing interest to practitioners of river management worldwide (Brookes and Shields, 1996). Many studies provide ecological (eg. Harper and Ferguson, 1995) or engineering solutions (eg. Jansen et al., 1979; Simon, 1995), however relatively few have examined the role that geomorphic solutions can play in river management and rehabilitation (eg. Sear et al., 1995).

Harper et al. (1995) propose that in terms of human impact there are three states of river environment. The first is a pristine river environment, which has endured minimal human activity. The aim for management is to protect these areas from human interference or minimise any future impact. Here, the environment is perceived to be too good allow it to significantly degrade and this state is therefore adopted as the ideal end point in a model for river rehabilitation. It is always much cheaper to prevent river damage than to attempt to rehabilitate reaches if they become degraded. The second type is the semi-natural river where there has been some human impact but not a major destabilisation or alteration. The goal in these rivers is to maintain or if possible enhance the existing qualities of the system as in such reaches relatively small efforts can yield high returns. Finally, there is the degraded river system where alteration has been followed by little natural recovery. The aim here is usually to stabilise the system artificially as natural recovery is perceived to be too slow due to the magnitude of the disturbance. The costs of such rehabilitation can be very high and, as environmental damage can be very severe, the desired outcome may be severely limited and expensive to achieve (Harper et al., 1995).

There are some further questions that need to be considered at a degraded site before rehabilitation should go ahead. These include;

Ecological improvement or aesthetic enhancement? Rehabilitating channels for aesthetic reasons is practiced in many parts of the world. The objectives of restoring the channel may be to improve visual attractiveness rather than necessarily to improve the natural ecological value of a channel. Aesthetic treatments includes reinstatement of pools and riffles, and development of more natural looking bank forms (Brooks and Sear, 1996).

Intervention or natural recovery? An important distinction in geomorphology is the assessment of channel stability and the identification of which channels are recovering and which are deteriorating. Enhancing the rate of natural recovery is often much more cost effective than full scale intervention. However, some systems do need intervention. For example, over a short time scale low energy environments may not have enough energy to adjust to a previous human-induced change. Also, straightened channels that have experienced substantial incision require the entire valley floor to be eroded by a similar amount for natural recovery to occur such that the channel and floodplain are back in equilibrium. Such a recovery is not possible over a short period of time (Brooks and Sear, 1996).

River rehabilitation can be undertaken to varying degrees. Full restoration is the complete structural and functional return to a pre-disturbance state. The management approach is by direct intervention, natural recovery or enhanced recovery. Partial rehabilitation is the partial return to a pre-disturbance structure or function using direct intervention or enhanced recovery. Enhancement is achieved by any improvement in environmental quality, mainly by using direct intervention.

Naturalisation is the development of a resource that did not previously exist (modified from Brooks and Shields, 1996). The aim of naturalisation is to determine the morphological and ecological configurations that are compatible with the contemporary magnitudes and rates of fluvial processes. This will produce stable, functionally diverse, self regulating geomorphological and ecological systems for the given set of processes

(including human utilisation of natural resources) associated with the contemporary environmental setting. Naturalisation objectives are broadly consistent with the objectives of rehabilitation (National Research Council, 1992) but they do not necessitate the disturbance required to re-establish pre-disturbance conditions ('full restoration'), or to move the system towards these conditions ('rehabilitation') (Rhoads and Herrick, 1996).

In essence, naturalisation is an attempt to produce an ecologically and geomorphically stable river system given the prevailing environment and current state of the channel. The idea is not necessarily to move towards the previous channel conditions but towards a condition with certain natural qualities but more compatible with the current channel's requirements. Rhoads and Herricks (1996), the proponents of this rationale, state (p.334):

> "Naturalisation emphasises that human utilisation of natural resources is a component of the current 'natural' environment of the region and that this factor must be considered explicitly in efforts to protect or improve the quality of existing environmental resources. It establishes stability, self regulation, and diversity of form and function as geomorphological and ecological goals of stream management, rather than a return to some unknown pristine state or the creation of an entirely new state, while at the same time providing an appropriate framework within which to establish the viability of re-establishing documented pristine characteristics in contemporary stream systems. Although naturalisation embraces the notion that emulation of the present condition of an undisturbed system may be an appropriate way to achieve ecological and geomorphological goals when human intervention is not an ongoing process, it also explicitly recognises that human modified elements may be an important component of 'natural' configurations in systems characterised by frequent human intervention."

This characterisation has lead to a shift in the focus of river management planning, particularly in the U.S.A. Previously, many managers of degraded river systems would have focused their efforts on restoring the channel to a state similar to pre-disturbance conditions. Now there is a realisation that human influences are going to continue regardless, so the direction of management strategies has involved retention but

stabilisation and aesthetic enhancement of the degraded channel system. Stabilisation is often achieved through engineering solutions and maintained by conservation strategies.

2.4 Issues and Problems in Australian River Management : An Overview

2.4.1 Stream Degradation in Australia

An increasing concern about environmental degradation in Australia in recent decades has also spread to the field of fluvial geomorphology and geomorphologists have become interested in studying the effects of European occupation on Australian river systems. Such work is providing an explanation for the current state of the riverine environments and is extremely important in assessing future directions for catchment management.

Knowledge gained from short-term fluvial process-form studies, together with that from studies of long-term river behaviour, is now being logically applied to the sensitive environmental management of degraded channels. In ideal situations a combination of Quaternary, recent, and current channel behaviour or characteristics and change can be examined to maximise the potential benefits of management studies (Tooth and Nanson, 1995).

Efforts to interpret the environmental history of early colonial Australia are severely hampered by a lack of written information about the nature of the contemporary landscape and the human impact upon it (Haworth et al., 1999). Evidence of changes as a result of European occupation is generally obtained from three major sources. Firstly, there is an oral tradition that includes local knowledge of specific examples of environmental change. Secondly there are documentary records, ranging from written descriptions to maps, survey data and photographs, and thirdly there is evidence of environmental change imprinted by the landscape itself, such as in palaeochannels, pollens and sediments (Finlayson and Brizga, 1995).

A brief summary of catchment degradation from post-settlement anthropogenic impacts was written by Warner (1984, p.135):

> "Australia has been settled by Europeans for two hundred years. However, the tempo of settlement and exploitation of a dry continent with erratic and changing hydrological regimes has caused considerable changes to occur. Most examples of channel metamorphosis have involved adjustments in width, depth and consequently width-depth ratios. Greater increases in width together with increases in depth, have locally caused braiding with steeper in-channel slopes, and more bed material in transit. Additionally, meander chute cut-offs have tended to reduce channel lengths locally and increase gradients. Very large floods have ruptured thresholds, as well as well as completely changing channel conditions and locations. In the moister east (of Australia) there has been large scale deforestation. Early forestry caused gullying and increased sediment loads in rivers."

Warner (1984), in examining the effects of European occupation on Australian rivers, identified indirect changes as well as the direct effects. Indirect changes occur at the catchment level and affect rivers through inputs into the system. Rural land use has often resulted in major disruptions to the water balance of a catchment and hence the hydrologic regime of the river system. Vegetation clearing, surface compaction by hoofed animals and cultivation have often lowered filtration and evapotranspiration, thereby decreasing concentration times and increasing run-off coefficients. Two centuries of western agriculture have altered run-off-sediment discharge balances directly causing changes in channel geometry, drainage network, flood frequency, flow duration, and other aspects of the hydrologic regime of streams (Eyles, 1977a, 1977b; Prosser, 1991; Riley and Erskine, 1995). The ensuing rationale behind many soil conservation and Landcare programs in upland catchments is the reversal of the hydrologic impacts of rural land use (NSW Landcare Working Party, 1991). Urban environments have had a greater impact still on catchment hydrology from the construction of impervious surfaces, drains and sewers, concrete channels and the like, however this has not been a significant problem, as yet, in the Nambucca catchment.

Direct effects deal specifically with alterations to river channels. Dams have had a major effect on river systems in Australia although, again, this has not been a factor in the Nambucca. The hydrologic regime of Australian rivers has been greatly affected by channelisation. Straightening of channels reduces channel length, reduces slope and

decreases form roughness. The combined result is a local increase in flow velocity, a reduction in concentration times, increasing peak discharges and, an initiation of bed degradation (Riley and Erskine, 1995). The impacts of channelisation have been exacerbated, in some instances, by the removal of large woody debris (LWD), which further reduces channel roughness. The removal of LWD has been carried out in NSW by the (then) Department of Water Resources and local councils (Erskine, 1990; 1992; Riley and Erskine, 1995).

Riley and Erskine (1995, p.25-26) conclude their paper on the human impacts on NSW rivers by stating:

> "While it is possible to say that the recent land use practices have altered the hydrologic regime of NSW coastal rivers it is not possible to quantify the nature of those impacts for all streams. The hydrology of a river is complex and single index descriptions of impacts are unlikely to convey an accurate picture of the changes that have occurred. However, at the risk of being (taken to task) for obvious exceptions, we offer the following generalisations:
>
> - lower flow regimes have been significantly decreased by irrigation in rural areas and increased by channelisation in urban areas
> - the low frequency floods are largely unaffected by human activities in large catchments in rural areas
> - floods have increased significantly in magnitude and frequency in urban areas
> - secular climate changes contribute to observed hydrological changes in many large catchments but it is difficult to disentangle the significance of this cause of hydrologic change from human impacts on the hydrologic regime
> - management of hydrologic impacts must be a catchment-wide exercise if it is to succeed
>
> The complex combination of natural and human induced changes in the hydrologic regime have implications for river and Total Catchment Management. Not every change in a river or catchment can be blamed on humans nor is natural variability the sole cause of change. Resource commitment to ameliorating 'undesirable' change has to be tempered with an understanding of the underlying processes-response system. 'You cannot fight nature'."

Despite all of the site specific, human-induced, catchment changes outlined above, Brookes and Brierley (1997) argue that studies on channel change in Australia understate the effects of indirect and diffuse human impacts on channel morphology, such as forest clearance, or the more subtle effects of altered riparian vegetation communities. This despite the fact that catchment-wide vegetation cover is one of the primary intrinsic controls on sediment supply and hydrology to a river, and despite being the control most susceptible to human alteration.

The historical record shows that in humid south-eastern Australia, vegetation clearance of slopes, floodplains and channel banks in the period following European settlement has had a major impact on channel form and behaviour. Brookes and Brierley (1997) speculate that distinctive geomorphic traits of some coastal rivers in southeastern Australia, such as bench development (eg. Erskine, 1986; Erskine and Livingstone, 1999), catastrophic channel widening (eg. Erskine, 1994), river avulsion (Brizga and Finlayson, 1990) and floodplain stripping (Nanson, 1986), may reflect the increased flood effectiveness associated with European clearance when river regimes were fundamentally altered from their pre-disturbance conditions.

2.4.2 Applied Studies on NSW Coastal Rivers

There are very few papers in mainstream journals that examine applied fluvial geomorphology in relation to NSW coastal rivers. In addition there are almost no reports that address the combined issues of Quaternary change, recent change, hydrology, sediment characteristics, riparian vegetation and, current management practices on a non-tidal NSW coastal river system such as this study on the Nambucca catchment. The exception are papers resulting from this study (Nanson and Doyle, 1999; Doyle et al., 1999)

Most of the recent papers dealing with applied fluvial geomorphology and NSW coastal rivers involve investigations of flood induced channel change (eg. Erskine and Bell, 1982; Erskine, 1986; Warner and Paterson, 1987; Nanson and Erskine, 1988; Erskine and Warner, 1988; Warner, 1991; 1995; Brooks and Brierley, 1997). In addition there have

been some studies examining the impacts of; specific floods (eg. Erskine and Melville, 1978), river training works (eg. Erskine, 1990; Nagel, 1995) and sand and gravel extraction (eg. Erskine et al., 1985).

2.4.3 Gravel Bed Rivers

Gravel-bed rivers are commonly associated with mountainous regions containing metamorphic rocks (Neill and Hey, 1982) and the size and shape of the bed material is crucial to the stability of the channel (Milne, 1982). The instability of bed material in gravel-bed streams is controlled by scour in a different way to sand and silt bed channels. Material of larger size or more oblong shape can armour the bed and control scour and can also control the location of pools and riffles (Hirsch and Abrahams, 1981; Clifford, 1992).

Due to their steeper slopes and higher energy it can be argued that human induced changes to gravel-bed rivers cause more dramatic problems than to sand or silt bed channels. Decreasing sinuosity and channel widening is symptomatic of human disturbance (Patrick et al., 1982). Retreating nickpoints due to artificial or disturbance-induced straightening leaves behind composite bank profiles in the form of cohesive silt in the upper and middle portion, whilst the lower bank is commonly comprised of unconsolidated gravel exposed by bed lowering. The fluvial entrainment of gravels renders the cohesive material above prone to mass failure (Thorne and Tovey, 1981). The failure of these cantilevers exacerbates the process of channel over-widening and the results in steep bank faces that exceed the thresholds required for stability (Millar and Quick, 1993). Well-vegetated banks can also fail in this manner if the bed level drops beneath the root mat of the bank vegetation or if gravel is entrained from within the root mat (Cohen, 1997). Undercutting leads to tree fall in the channel and the subsequent flow divergence can exacerbate the problem of bank erosion (Rankin, 1980). However, it should be noted that this is usually not a problem unless the river does incise and undermine the vegetated banks.

2.4.4 Theory and Practice of Channel Rehabilitation and Management

The realisation that humans have greatly altered river channels is not a recent occurrence. There has been a limited understanding for quite some time that human occupation, particularly agricultural practices, can have a dramatic impact on natural landscapes:

> "In the course of my fieldwork in the rural districts I am constantly struck with the effect of human culture on the streams. Hardly in any particular has man in a settled country set his mark more conspicuously on the physical features of the land." - G.W. Lamplugh on the state of rivers in the British Commonwealth (1914, p.61)

However, in most cases the need for channel rehabilitation and catchment management is identified from aesthetics. We observe that the physical appearance of a river is in decline yet our understanding of the causes of, and solutions to, the physical changes identified are sometimes misguided due to a lack of understanding of how rivers actually work.

> "Many times human perceptions of geomorphic habits are fallacious. Three types of misconceptions are (1) a perception of stability, which leads to the conclusion that any change is not natural, (2) a perception of instability, which leads to the conclusion that change will not cease, and (3) a perception of excessive response, which leads to the conclusion that changes will always be major... Such perceptions can lead to litigation and unnecessary engineering works." - S.A. Schumm (1994, p.129)

In examining possible solutions, attention must be given to understanding fluvial processes. The fact that humans still have misconceptions as to how fluvial systems operate means that the era of management is not a guaranteed success simply because we now want to look after our waterways. Environmentally sensitive stream rehabilitation and management is in its infancy and stream managers everywhere are still coming to terms with balancing site specific management with holistic, ecologically sustainable, catchment management.

Many environmental problems result from a failure to recognise the nature of the fluvial system and its interaction with the biological system. Channels modified for flood control often experience severe environmental degradation due to erosion and sedimentation, loss of vegetation cover, reduction in the amount and value of habitat, and a decline in aesthetic values. Many negative environmental impacts can be avoided by designing (or reconstructing) channels that are in harmony with changed fluvial conditions and that minimise disruption to the existing fluvial and biological conditions (Brookes, 1991).

It has long been understood that the three major technical components of any project involving a natural system, whether or not connected with rivers, are economics, engineering and environment. Although environment is a major component, economics is usually a deciding factor influencing the final outcomes and the methods implemented.

2.4.4.1 Community Involvement - The Australian Way

An examination of overseas rehabilitation programs highlights the large budgets given to projects in relatively densely populated developed countries. Such costs cannot be borne in rehabilitating rural streams such as in the Nambucca catchment in Australia which supports a population of only a couple of thousand people. Budget restrictions and a consequent preference for 'soft' engineering approaches have caused Australia to develop an unusual system of stream management where the majority of management strategies are community driven. In the country areas of Australia, large farms and small populations have meant that management plans cannot achieve on-the-ground management without community involvement. This means that no matter how good the scientific research is - no positive action will occur unless the landholders take part and support proposed initiatives (Good and Burston, 1996). This requires residents and agencies to share information and reach a common consensus regarding the nature of the problem and what should be done.

The value of landholders' experiences can be undervalued, but such experience must be utilised in Australia due to the isolation of some rivers and the lack of data available on channel change (Martin and Lockie, 1993; Good and Burston, 1996; Gardiner, 1996; Outhet, 1996). Involvement of the community does more than merely provide anecdotal evidence for channel change. It can lead to issues of stream management being raised

that are not initially appreciated by scientists or government agencies. For example, a landholder may be able to report a decline in fish species, or problems in growing a particular plant species. Without this input, such problems may not be dealt with at all in the management process. Community input can also provide important follow-up support enabling river works to be repaired or maintained.

However, there are also examples of projects going wrong when they are based solely on community derived information (Finlayson and Brizga, 1995). The Nagoa River, Queensland, and the Avon River, Victoria, have both undergone some change since European settlement. In both cases, records documenting channel character had been ignored in place of an oral history of change. Interpretations of river channel behaviour from the documentary record and field evidence on the Avon and the Nagoa suggest somewhat different histories of change to those perpetuated in oral folklore (Finlayson and Brizga, 1995).

In the oral tradition, erroneous ideas can be given legitimacy by being quoted frequently. Beliefs about river channel change stemming from the oral tradition have had a considerable impact on both the rhetoric and practice of river management. The revelation that erosion is not necessarily unnatural and that land loss has been much less dramatic than earlier thought make the arguments for a comprehensive and costly bank stabilisation program less compelling. The oral tradition may become widely and uncritically accepted because it lends support to the arguments put forward by landholders who want public money spent on bank erosion affecting their land. Surprisingly, there may never have been an analysis of the economic, environmental or social benefits of river management works on certain rivers despite large amounts of public money being spent over a long periods (Finlayson and Brizga, 1995).

The most useful form of community involvement comes from on-the-ground implementation of rehabilitation works. Rivercare works established on the Manning River (Gardiner, 1996) facilitated close liaison between the Department of Land and Water Conservation (DLWC) and land holders. Morphological features and channel histories were written onto enlarged aerial photographs. Rehabilitation options were then generated and the selection of the preferred method was selected on environmental and

economic grounds. The process was assisted by the *Riverwise* program which educated land holders about stream processes and encouraged them to become stream managers (Outhet, 1996).

There are now manuals available (eg. Raine and Gardiner, 1995) which provide guidelines for community groups and river managers to follow for the ecologically sustainable management of rivers and riparian vegetation. The manuals not only outline approaches and methods for river management, but also provide background educational material on the Australian landscape and the effect of European settlement.

The implementation of imported ideas was the major engineering approach to river management in coastal NSW after the 1949-1955 floods (Erskine, 1990; Nagel, 1995). It was assumed that erosion control techniques successful in Europe would have the same benefits in Australia. To some extent the river improvement works (eg. those in the Hunter catchment) were successful in stopping further erosion at individual sites. However, the river improvement works have had no effect in controlling off-site erosion. Many overseas designs fail to take into account that Australian rivers are often ephemeral with a wide range of flows (Wasson et al., 1996). The range of flows makes suitable channel widths and alignments difficult to determine (Nagel, 1995).

2.5 Sediment Related Problems of the Nambucca Catchment

Instability of the gravel-bed streams of the Nambucca catchment has been of major public concern since the catastrophic floods of 1949 and 1950. Since then, lateral migration, stream widening, bed-level fluctuation and the accumulation of gravel have all been cited as major indicators of a river system in disrepair (Raine, 1994; Resource Planning, 1989; Thoms, 1994; Department of Water Resources, 1994; Department of Land and Water Conservation, 1995; Water Conservation and Irrigation Commission, 1970; Water Resources Commission, 1979).

Gravel extraction has been carried out consistently since settlement, and was particularly prevalent in the period from 1950 to 1996. The consistent removal of gravel was thought to alleviate bank erosion problems and to provide supplementary income to landholders

to use for management of the degraded streams (Water Resources Commission, 1979; Resource Planning, 1989). Numerous short-term studies have attempted to assess the impacts of gravel removal from tributaries in the Nambucca catchment (Resource Planning, 1989; Thoms, 1994; Lagasse, 1994), but there have not been any long-term studies that have measured streambed sediment or analysed the channel history to determine the appropriateness of gravel extraction in the Nambucca catchment.

After detailed consultation with many of the Nambucca Shire residents (by written questionnaire - Appendix 2), it is evident that bank erosion is of major concern. It results in the loss of prime alluvial flats for agriculture, which forms the main source of income for nearly all the riverine residents in the valley. There are many reasons as to why bank erosion is rampant in the streams of the Nambucca catchment. The first and most obvious reason is the lack of suitable stream bank vegetation (Raine, 1994). Ironically, whilst a lack of stream bank vegetation may have started the problem, the current intermittent spacing of trees along the banks may, in places, contribute to the continuation of erosion. Undercutting of isolated large trees can cause these trees to fall into the stream, deflecting flow into the banks (Department of Water Resources, 1992). This problem can be significant in the Nambucca catchment due to the presence of fine gravels commonly at or near the base of the banks. Such gravels can be eroded more easily than cohesive fine sediment, leading to undercutting and bank failure.

Undercutting may also be caused due to the removal of bed-control structures or by channelisation (Galay, 1983). Furthermore, channelisation can result in a steepening of the long profile of the bed, which increases stream velocity and the tractive forces on the bed and banks. The removal of bed control structures can eliminate the stepped pool and riffle sequence, resulting in a uniform bed profile. The result is less effective energy dissipation with subsequent erosion leaving the banks prone to undercutting (Petit et al., 1996). The loss of natural sediment traps due to removal of the pool and riffle sequence makes the bed material unconsolidated and relatively mobile.

Lateral channel movement and sediment transport means that the streams widen as the fine material, once stored in the banks and floodplains, is transported downstream to the tidal zone and beyond, leaving the gravels behind. These gravels covering the bed give the appearance at low flow of a system 'choked' with excessive bed material. A lack of

sediment traps allows the pools to fill with gravel bars free to move as large sediment slugs (Kondolf et al., 1993). Changes in channel geometry as a result of bank erosion and gradient steepening can cause major changes to the sediment transport regime of the stream system (Andrew and Parker, 1987).

2.5.1 Previous Reports on Sediment Management in the Nambucca Catchment

The problem of severe channel erosion during the past 30 years has lead to a number of reports by government departments regarding the streams of the Nambucca catchment. The earlier reports were based on flood mitigation works (eg. Department of Public Works, 1974; Gutteridge Haskins and Davey, 1981), costed river improvement works (eg. Water Conservation and Irrigation Commission, 1970; Water Resources Commission, 1979), and flood history studies (eg. Department of Public Works, 1980, 1983). In the last decade, government departments and consultants have directed studies more at assessing catchment resources in relation to river preservation and/or restoration (eg. Resource Planning, 1989; Department of Water Resources, 1994; Thoms, 1994: Raine, 1994; Department of Land and Water Conservation 1995; 1996).

The three reports from the 1970's mentioned above identified the main problem in the catchment as overgrown vegetation along the channel, which was believed to divert flow, erode the banks, slow floodwaters and cause enhanced flooding. This approach, although correct in identifying flow diversion into banks as a cause of erosion, neglected to acknowledge the fact that removal of stream bank, streambed and floodplain vegetation acts to reduce roughness and increase velocities during flooding. By increasing velocities during flooding the banks and floodplains become vulnerable to erosion. More recent studies also propose clearance of in-stream vegetation but endorse the construction of sediment traps to maintain a pool and riffle sequence and a sinuous channel (Department of Land and Water Conservation, 1995, 1996).

Resource Planning (1989) carried out a study on the gravel resources of the Nambucca River (North Arm) and Missabotti Creek. This study, although cited in subsequent reports, was heavily criticised by residents (Thoms, 1994). Among a number of omissions it failed to provide detailed measurements of the bedload size and lithology.

Almost all of the aforementioned government and consultancy reports are centred on North Arm and Missabotti Creek. Whilst widely accepted as being amongst the most seriously degraded areas of the catchment, the focus on these two streams has meant that the remainder of the catchment has been largely ignored. There is little or no information available on streams such as Buckra Bendinni Creek, South Arm, Warrell Creek or Deep Creek. In particular, there is no sediment size data.

2.5.2 Gravel Extraction in the Nambucca Catchment

The issue of gravel extraction is one of the most controversial issues in the catchment. Debate exists between residents themselves, and between residents and government departments over the effect of gravel extraction, the necessity of gravel extraction and the volume of gravel to be removed. Until the mid-1980's records of the amount of gravel extracted were so poor that estimates could not be made with any confidence. The Department of Land and Water Conservation (1995) estimated that the amount of gravel extracted from 1987-1992 was in the order of 120,000 m^3 annually, whilst the 1994 amount was significantly lower, in the order of 50,000 m^3. Resource Planning (1989) estimated that 20,000-30,000 m^3 per annum was extracted by private contractors annually. Official records from the Bureau of Mineral Resources from 1987-1993 can be seen in Table 2.1, which shows that an average of 95,444m^3 was extracted per annum in this period. These figures do not include any unofficial extraction of gravel. Using the official extraction figures, plus 5%, a mean figure of 100,000 m^3 per annum means that every year there is enough gravel extracted to leave a pit 10 metres wide, 1 metre deep and 10 kilometres long.

Considering that the extraction is mostly carried out on North Arm and Missabotti Creek (with a combined distance of approximately 80 km), it is fair to say that over 16 years enough gravel may have been extracted to cut a 2m x 10 m trench along the entire non-tidal sections of North Arm and Missabotti Creek. This would total 1,600,000 m^3. However, a survey of residents (Appendix 2) has shown that gravel extraction on North Arm and Missabotti Creek has been occurring at least since the end of World War I, with the periods 1970-1974 and 1989-1994 noted among many of those surveyed as years when gravel was extracted from their property. Support in the community, and the reliance on gravel extraction for income and stream management, makes it clear that the problem is complex.

Despite the massive amounts of gravel that have been extracted over a long period, the visual appearance of the modern channels indicates a system that has an *oversupply* of gravel. This appearance, however, is due to natural adjustments that accompany disturbance on such an enormous scale. Since the catastrophic floods of 1949 and 1950, stream widths and depths have increased, and as the stream laterally migrates the gravel stored in the banks and floodplain enters the stream. The fine material accompanying the gravel in the floodplain is more readily transported to the tidal limit and beyond leaving an extensive cover of gravel over the streambed (Doyle et al., 1999).

Bed elevation changes and a decline in the water table can give the appearance of an over-accumulation of gravel, particularly if there are no bed controls. If the channel sinuosity decreases, then there is also a shorter length of river to support a greater amount of gravel in transport. There will also be more gravel to transport as channel straightening involves bank erosion and the release of floodplain gravel into the stream.

A 1994 Draft Plan of Management (DLWC 1994) endorsed gravel extraction in areas where there is no evidence of overall channel enlargement. In these areas it was recommended that gravel be extracted only above low-water level.

North Arm and Missabotti Creek have the most sought-after gravel type in the catchment (anecdotal evidence based on the commercial use of these gravels), but they are also the most severely eroded streams. This has lead to numerous reports examining the management of these streams (eg. Department of Water Resources, 1994; Thoms, 1994; Resource Planning, 1989; Nambucca Valley Association, 1990; North Arm Landcare Group, 1990). Resource Planning (1989) stated that there were over 20 sites on North Arm and Missabotti Ck that either had permits or were potential sites for gravel extraction. It is important to examine differences in the amount and type of gravel on these two streams and to compare these to other streams in the catchment.

The Department of Water Resources (1990) emphasised the Department's wish to endorse extraction at a sustainable level. Reviews by the Nambucca Valley Association (1990) and North Arm Landcare Group (1990) both point out the uncertainty involved in attempting to ascertain what is a sustainable level. Whilst sustainable yield is a logical

concept for clearly renewable resources such as vegetation, there is uncertainty as to how a sustainable gravel yield can be calculated given that hillslope or headwater derived bedload in these streams is a finite resource.

2.5.3 *Gravel Extraction Literature*

Sand and gravel mining from riverbeds is one of the major sources of construction aggregate. The dearth of available information on the effects of gravel extraction is a major hindrance to those wishing to apply the findings of previous research to current work. Many studies on this topic are not published although some can be found in the archives of government departments both in Australia and overseas.

Substantial mining activity reduces the amount of total sediment throughput and can cause severe degradation problems upstream and downstream (Lee et al., 1993). In the available literature, most attention is given to streambed lowering and the loss of bed armour as consequences of inappropriate gravel extraction. Chang (1987) indicates that gravel extraction can significantly distort the natural equilibrium of stream channels, inducing channel change during major storm events.

Lagasse et al. (1980) pointed out that the impact of gravel mining on river stability has not been fully investigated, yet the effect of gravel armour on streambed stability has received considerably more attention. By way of hydraulic sorting the coarser fraction of bed material naturally develops armour over the finer layers. This armour can prevent excessive bed scour and sediment movement, which results in the stabilisation of the bed and banks. Removal of the gravel armour means the loss of erosion control and an increase in bed material transport. Gravel armouring can also help limit the scouring around river works, such as dykes and groynes, and around bridge pylons (Lagasse et al., 1980).

Bed degradation from over-extraction alters bed morphology and bed forms that provide important biotic habitats. It lowers floodplain water tables, reduces the frequency of overbank flows and wetland inundation, changes bed-material size composition, causes bank collapse, increases bar mobility, increases the frequency of bed material movement and causes the destruction of aquatic and riparian vegetation (Erskine et al.,1985; 1996).

Gravel mining can have a range of effects on a stream, from minimal change in water and sediment discharge to completely halting both. Removing gravel from the streambed causes a local lowering of the bed resulting in overall downcutting of the channel upstream of the mining operation (Bull and Scott, 1974). Petit et al. (1996) describe how large amounts of gravel extracted from the Miribel Canal in France since the 1970's has resulted in a dramatic lowering of the riverbed and the destruction of armoured riffles. Erosion from the main channel can also result in lowering of the local base level of tributary channels, thereby initiating erosion along the tributary streams (Galay, 1983). Deepening of the stream channel due to extraction increases channel capacity, which allows more water to remain in the channel during floods. This results in a reduction in floodplain inundation but increase in the flow velocities, making the banks more susceptible to erosion (Bull and Scott, 1974).

When gravel is removed from several locations along the bed of a stream, removal often exceeds the rate of replenishment from the natural watershed (Bull and Scott, 1974). Erskine et al. (1985) point out that the prevention of riverbed degradation is vital. Therefore, extraction rates (from the channel, bar and benches) must not exceed the rate of replenishment of fractions of the same size, particularly where armouring is present. They go on to emphasize that it is important to know the nature of all channel controls, not just armouring, as clay and bedrock outcrops and engineering structures often act as local base levels and restrict lateral movement of the stream. Erskine et al. (1985; 1996) have stressed the importance of monitoring bed armour and sediment replenishment rates in studies of the Hunter and Goulburn Rivers. On the Goulburn River, former extraction sites were monitored and it was found that, over time, the bed armour returned to that of the previously undisturbed conditions. However, this would not compensate for effects on the stream as a result of the loss of armour and over-extraction.

It was calculated that the replenishment rate of gravel was so low that extraction rates of over 300t/yr would exceed the replenishment rate. The current annual average rate of extraction on the Goulburn River is 14,000 m^3. This rate has made a substantial contribution to the widening of the channel in addition to other morphological changes (Erskine et al., 1996).

In most rivers that experience in-stream gravel extraction there are other human influences that could be impacting upon channel stability. However, changes in stream equilibrium solely from gravel extraction is possible when the scale of extraction is excessive relative to bedload supply (Kondolf et al., 2002). There are many cases where the amount of gravel extracted exceeds supply with channel instability resulting (eg. Erskine et al., 1985; Kondolf and Swanson, 1993; Kondolf, 1995). In areas of Australia east of the Great Dividing Range, low sediment yields infer that extraction alters thresholds, reducing the availability of transportable material (Nanson and Hean, 1987).

Results of a study on the Hunter River (Erskine et al., 1985) imply that the removal of armoured gravel riffles would result in rapid bed degradation. The calculated mean annual bedload yields for the Upper Hunter indicated that extraction rates were many orders of magnitude higher than the replenishment rates, a process which would lead to undoubted channel enlargement. Extraction at that rate would remove one metre of sediment from the bed of the investigated reach each year.

There are concerns, however, as to how much of the blame for channel instability should be attributed to gravel extraction. Erskine et al. (1985) emphasise that 1m of bed degradation had occurred at Aberdeen on the Hunter River since the early 1970's in a reach where there was no gravel extraction. Zero level on the stream gauge was lowered by 1.53m in 1970, thus indicating that the upper Hunter River was experiencing a period of degradation that was possible due to anthropogenic influences but unrelated to gravel extraction.

Lagasse et al. (1980 p.400-402) stated:

> "A concentrated, long term data gathering effort would be required to clearly delineate the impact of gravel mining on river system stability. Available data are sufficient, however, to show a possible relationship between gravel mining and the development of divided flow reaches through chute channel enlargement...the available data are not sufficient to establish a direct cause and effect relationship between gravel extraction and river instability. The correlation is sufficient to serve as a warning of a potentially serious problem...some or even all of the changes coincident with gravel extraction examined may have occurred without the removal of

> gravel from the river bed (eg. the development of divided flow reaches is influenced by numerous natural and man made processes) but the observed changes may have been increased in magnitude or accelerated by the removal of gravel armour from point bars. The writers feel strongly that the evidence presented is sufficient to conclude that indiscriminate removal of gravel from riverbeds may be activating far-reaching changes in stream morphology."

Erskine et al. (1985 p.83) made the following closing comments on the environmental effects of gravel extraction industries:

> "The environmental impact of a proposed extractive industry or large excavation operation includes effects on sediment (bed-load material) transport continuity, channel controls or sediment storages. Sequential vertical aerial photographs and various maps can be used to determine rates of lateral migration and point bar accretion and changes in the location and size of channel controls, the permanence of riffles and bars, areas of unstable river banks and preferred zones of deposition. Data on bed material size, bed material load discharge, armouring, bedrock outcrops, the volume, the particle size, stratigraphy and location of excavated material and recent channel changes must be examined in environmental impact reports if such documents are to allow even an elementary assessment of the impact of a proposed operation on river system stability. Furthermore, an individual site should not be considered in isolation of other operations in the same reach of the river."

Erskine et al. (1996) suggest that gravel extraction only proceed when extraction benefits the stream (i.e. for the correction of alignment instabilities, protection of public and private assets, removal of zones of heavy deposition, and the maintenance or improving of habitat values). Extraction should also be limited to circumstances when it can be demonstrated that no long-term irreversible impact on the river will occur, or that extraction is within the available replenishment rates. In all circumstances extraction should always be undertaken according to approved guidelines.

Table 2.1: Rates of gravel extraction in the Nambucca catchment 1987 - 1993
(Source: BMR Extractive Industries Returns. Values given are in m^3).

Name	Code	Purpose	1987/88	1988/89	1989/90	1990/91	1991/92	1992/93	Average
Sand and Gravel									
663 JD and BI Fortesque	200 Gravel	Processed	39 000 m^3	29 130	22 290	17 000	18 564	16 250	23 706
5161 Austone Pty Ltd	200 Gravel	Processed	5 390	5 155	5 352		5 858		5 349
5161 Austone Pty Ltd	300 Cons. Sand	Processed	2 864	2 062	3 445	2 286	2 518	2 328	2 586
5161 Austone Pty Ltd	190 Dec. Agg.					5 275		5 835	5 555
5302 Wia-ora Sand and Gravel	200 Gravel	Processed	400	5 000	6 000	20 155	7 000	31 260	11 636
5302 Wia-ora Sand and Gravel	300 Cons Sand.	Processed				6 047		9 433	7 740
5972 Nambucca Earthmovers	200 Gravel	Processed		13 515					13 515
5979 JA and KF Welsh	500 Gravel	For Fill					548		548
5979 JA and KF Welsh	400 Gravel	For Roads		7 460	9 395	2 856	10 416	1 806	6 387
1136001 Nambucca Shire Council	400 Gravel	For Roads	10 000	20 824	35 000	27 000	42 875	23 150	26 475
1136010 RTA	500 Gravel	For Fill					65 000		65 000
1136050 Forestry Commission of NSW	400 Gravel	For Roads	300			310	260	1 625	624
Total Sand and Gravel			**57 954**	**83 146**	**81 492**	**80 929**	**153 039**	**91 687**	**91 375**
Other									
1136001 Nambucca Shire Council	402 Granite	For Roads		17 528	2 000				9 764
1136010 RTA	501 Shale	For Fill						500	500
1136020 Public Works Department	1 Granite	Over 75 mm			3 625				3 625
1136050 Forestry Commission NSW	401 Shale	For Roads			765				765
Total Other				17 528	6 390	0	0	500	4 884
Total All Extractive Industries			**57 954**	**100 674**	**87 882**	**80 929**	**153 039**	**92 187**	**95 444**

3. CLIMATE, HYDROLOGY AND LAND USE IN THE NAMBUCCA CATCHMENT

3.1 Geology

The Nambucca catchment is dominated geologically by the Lower Permian Nambucca Beds. These beds comprise of slate, phyllite, schistose sandstone and schistose conglomerates. The Department of Mineral Resources (1988) further classifies the local geology into unnamed phyllites (phyllite, schist, rare metabasalt) and the Pee Dee Beds (cleaved siltstone, minor diamictite). The unnamed phyllites dominate the northern, central and western parts of the catchment, whilst the Pee Dee Beds outcrop in the south and southeast of the catchment. A small number of Tertiary basalt caps appear on some peaks in the far west of the catchment (Figure 3.1).

The phyllite rock that predominates is relatively soft and weathers readily. Fluvial transport produces fine textured alluvium within the floodplains. Intruded quartz bands, more resistant than the phyllite or schistose sandstone, erode to form quartz cobbles. The headwaters of the catchment are characterised by phyllite, schistose sandstone and quartz boulders.

During sediment transport quartz sediment remains as cobble-sized fragments, whereas downstream abrasion causes rapid breakdown of the phyllite and schistose sandstone. Resource Planning (1989) stated that the greater resistance of closely fractured quartz means that cobble sized quartz gravel makes up the bulk of the bedload. The sand and silt weathered from phyllite and the schistose sandstone form the overbank deposits and in-stream fines.

The major geological fault in the catchment is the Demon Fault, which parallels the upper sections of Taylors Arm. The Department of Mineral Resources (1988) inferred that there is a syncline dividing the streams of North Arm and Missabotti Creek and an anticline between Taylors Arm and Warrell Creek, with the folds parallelling these streams. Where the syncline between North Arm and Missabotti Creek disappears downstream, Missabotti Creek then flows south to meet North Arm.

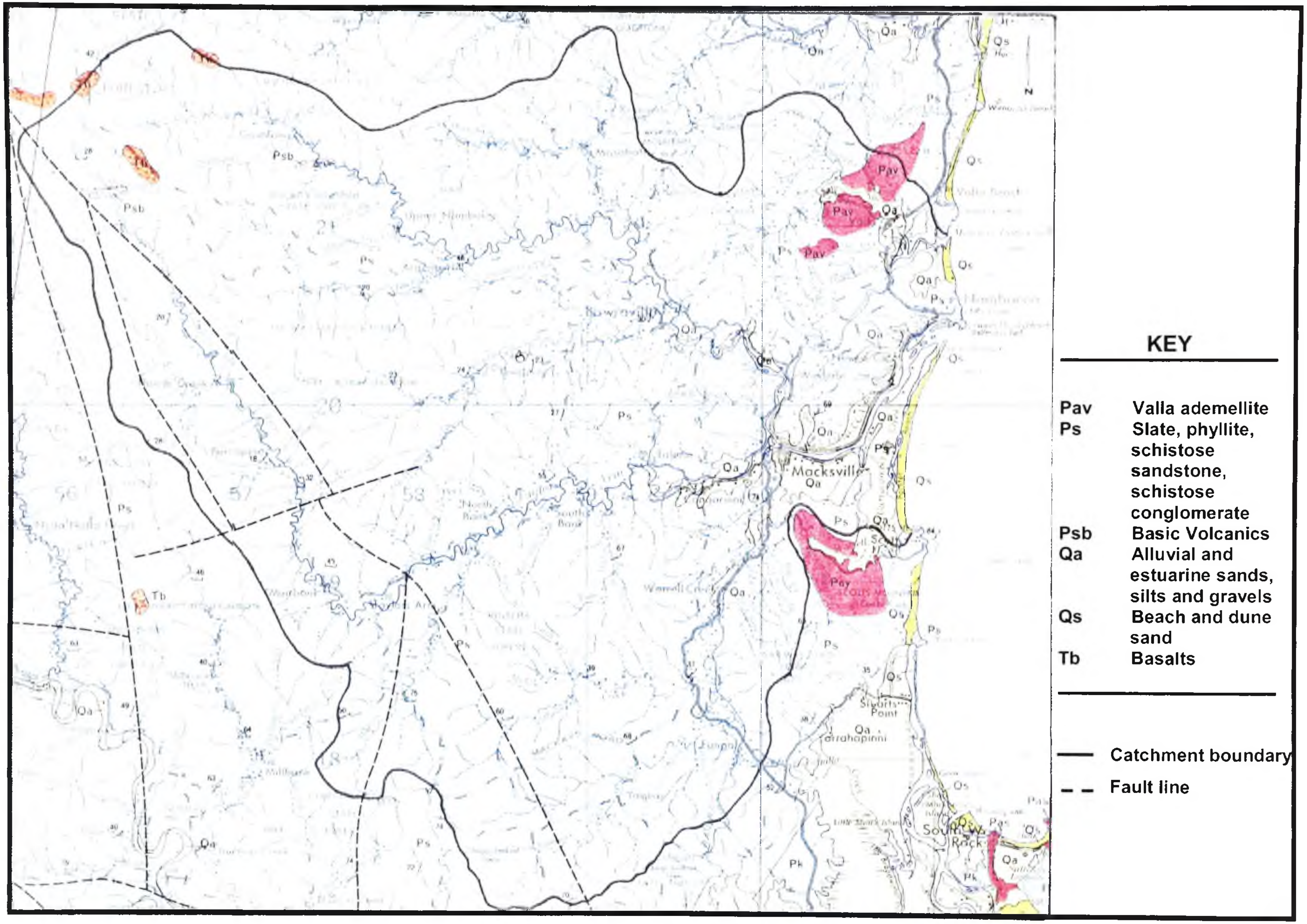


Figure 3.1: Geology of the Nambucca River catchment (DMR, 1971)

Figure 3.1 shows the regional geology as depicted on the 1:250,000 geology map prepared by the Department of Mineral Resources (1971). Unfortunately there are no descriptive notes to accompany the geology map contributing to a general paucity of information relating to the geology of the Nambucca catchment. Of the approximately 40 references to the local geology held in the Department of Mineral Resources Library, the majority relate to aspects of mineral exploration.

Cameron et al. (1987) prepared an analysis of the geological aspects that needed to be considered in preparing the Nambucca Local Environment Plan. The majority of that report deals with the mineral resource of the valley and presents only a sketchy outline of the regional geology.

A detailed analysis of the metallogenic characteristics of the 1:250,000 map sheet area has been undertaken by the Geological Survey of NSW (1992), but the report only devotes about four pages to the geology of the Nambucca geological block.

3.2 Soils

As part of its program of mapping the soils of NSW, the Department of Land and Water Conservation prepared a 1:100,000 map and report relating to the soil landscape units of the Macksville-Nambucca area (Eddie, 1997).

Soil landscape units are defined as areas of land that *"have recognisable and specific topographies and soils that are capable of presentation on maps and can be described by concise statements"* (Eddie, 1997). Because the same processes that form the landscape are also causal factors in the formation of soils, there is a strong correlation between soil characteristics and landform. This interrelationship allows a soil landscape unit to define a particular arrangement of soil types and their occurrence in the landscape. Soil landscape units fall into ten broad groups that are named after the main formation processes, which are summarised in Table 3.1.

Table 3.1: Soil landscape units of the Nambucca catchment.

Residual soil landscape units (1,300 ha) are dominated by sites where deep soils have formed from *in situ* weathering of the parent materials. Residual soil landscapes are found adjacent to the estuarine deposits in the eastern areas of the Nambucca catchment and typically have level to undulating elevated topography and include broad crests, gentle hill slopes and terraces. Stream channels are usually poorly defined and have limited capacity to transport sediment out of the landscape.
Colluvial soil landscape units (76,300 ha) are affected by areas of mass movement although erosional processes may be dominant. Parent material includes scree, mudflow and landslip deposits. These units are usually found on steeper slopes along the ridges within the Nambucca catchment.
Erosional soil landscape units (45,900 ha) have been formed by the erosive action of running water on hill slopes. Soil depth is usually shallow and the soil may be derived from water transported parent material or by *in situ* weathering.
Transferral soil landscape units (1,600 ha) comprise deep deposits of eroded soil and parent material washed down from the adjoining hill slopes. These units are found at the foot of the hill slope and tend to merge with the alluvial soils adjacent to rivers and creeks.
Alluvial soil landscape units (12,88ha) are formed by deposition of sediment transported down the valley by rivers and streams. Soils are usually deep and contain well-defined strata. These soil landscape units form the floodplains adjacent to the rivers in the Nambucca catchment.
Aeolian and barrier soil landscape units (900 ha) is a complex of sandy soils formed by the actions of sea level change and wind. As the name implies, these soil landscape units are found along the coastal fringe of the Nambucca catchment and comprise dunes and tidal flats.
Beach soil landscape units (600 ha) are derived from material deposited and reworked by wave action.

Estuarine soil landscape units (300 ha) occur where rivers enter a large body of tidal water. They comprise the soils found in estuaries, tidal flats and coastal lagoons.

Swamp soil landscape units (2,200 ha) are typically subject to seasonal waterlogging and often contain high levels of organic matter. These units are found in coastal swamps and lagoons.

Disturbed soil landscape units (100 ha), as the name indicates, are areas where the land surface has been substantially altered by human activity and where soil strata have been intermixed.

3.3 Land Use

An analysis was undertaken of the land use characteristics of the Nambucca catchment and the changes that have occurred over time. Aerial photography was used for analysis to provide a record of the major changes that had occurred in land use, vegetation cover and soil erosion status of the landscape. The three dates chosen were:

1942 - Representing the earliest aerial photography of the valley. Unfortunately the photographs available for analysis only covered parts of the catchment.

1956 - Representing conditions after major changes had occurred as a result of major floods in 1949 and 1950.

1991 - Representing a recent complete coverage of the valley.

The analysis involved detailed inspection of stereo pairs of aerial photographs and mapping of landscape attributes for a wide range of land use, vegetation and erosion characteristics. This interpretation was checked against the assessment of individuals who had a thorough knowledge of the catchment as well as being checked against independent mapping carried out by others (eg. NSW Forests).

Table 3.2 summarises the available land use statistics for the total area mapped for 1956 and 1991.

Table 3.2: Land use areas in Nambucca catchment: 1956 and 1991

Land Use	Area 1956 (ha)	Area 1991 (ha)	Difference 1991-56 (ha)
Timber — Native forest	17,497	17,315	-182
Timber — Native forest logged	47,410	46,499	-911
Timber — Regrowth	11,470	16,947	5,477
Timber — Windbreak and woodlots	546	1,313	767
Timber — Road reserve	202	240	38
Timber — Swamp	30	54	24
Grazing — Native & naturalised pasture	41,093	35,817	-5,276
Grazing — Improved pasture	30	212	182
Grazing - Sedge/fern/rush & other	5	44	39
Horticulture	867	713	-154
Mining and quarrying	2	11	9
Urban — Residential	90	83	-7
Recreational	0	11	11
Water	340	311	-29

The main statistic of interest in Table 3.2 is the reduction of the area, between 1956 and 1991, of native and naturalised pasture by about 5,000 ha whilst the area of timber regrowth increased by about the same amount. This apparent conversion of grazing land to regrowth timber is in line with anecdotal evidence from landholders in the valley who describe a decline in dairying and dry stock farming associated with changing economic conditions. There was also a reduction in the area of logged native forest by about 900 ha and an increase in the area of planted woodlot or windbreak by about 750 ha. Overall these statistics present a picture of a valley in which there has been a substantial reduction in pasture and an increase in forest cover over a 35-year period.

3.3.1 Land Use Changes in the Nambucca Catchment

The Nambucca catchment has had a relatively short history since European settlement began in the mid to late 1800's and there is clear evidence of widespread changes occurring since that time. The major trends and events have included European

settlement of the Nambucca catchment, which started in the nineteenth century with the arrival of "cedar getters" (logging) that were working in the Nambucca as early as 1833 (Campbell, 1969). Organised cedar logging in the 1840's was only short lived. After the successful crossing of the bar of the Bellinger River the dealers and sawyers left the Nambucca in early 1843. It was during the second period of logging that permanent white settlement, which can only be dated to 1856, began on the Nambucca (Townsend, 1993).

Although it was to become a rich source of timber with its rosewood, mahogany and especially its red cedar, the Nambucca confronted European settlers with the immediate problem of clearing the land. Eucalypt forest dominated the less fertile uplands. Blackbutt grew to massive proportions and spotted, grey and red gums were common. Beneath these large trees were smaller trees such as river oaks. In the upper reaches of the valley, tussock grass flourished but kangaroo grass was common at lower levels, especially on the coastal margin (Raine, 1994).

Logging operations occurred on the on the higher slopes and ridges but was restricted in intensity until after the second world war when war surplus trucks and tractors provided the technology for more intensive logging operations and the exploitation of previously inaccessible areas. The ringbarking and clearing of trees on the lower slopes was undertaken to create grazing land, which was primarily used for dairy cattle. Again, the availability of tractors after the Second World War allowed more intensive clearing and provided the means to plough and develop hillslopes.

Floodplains were cleared to allow cropping on the fertile alluvial soils, but the decline of the dairy industry since 1970 has allowed considerable areas of cleared land to return to open woodland cover or forest (Table 3.2). Forestry continues to be an important industry and the total area of timbered land is thought to be larger now than it was in 1940.

Unfortunately there is very little information on the details of vegetation cover in the Nambucca catchment at the time of European settlement. Based on the topographic, soils and climatic characteristics of the valley it may be assumed that the whole valley was forested and that the remaining forests are representative of the forest cover, which occurred in the hill country.

The detailed land use mapping of the Nambucca catchment has shown land use, vegetation cover and erosion status through aerial photography taken in 1942, 1956 and 1991. Some major aspects of catchment condition and changes that have occurred between 1956 and 1991 are as follows:

- by 1991, 63% of the catchment was forested (rainforest, wet sclerophyll and dry sclerophyll)
- a further 32% was described as containing scattered trees, clumps of trees or woodlots.
- there was a significant reduction (33,000 ha) in the area of ringbarked trees (identified from the photographs as clusters of dead trees and tree stumps) in 1991 compared to 1956.
- the area that appeared to be ringbarked trees in 1956 has reverted to scattered trees (20,500 ha), trees in clumps (3,700 ha) or wet sclerophyll forest (6,700 ha).

The area of native and naturalised pasture has been reduced by about 5,000 ha while the area of timber regrowth increased by about the same amount. This apparent conversion of grazing land to regrowth timber is in line with anecdotal evidence from landholders in the valley. Reduction in the area of logged native forest by about 900 ha, and the increase in the area of planted woodlot or windbreak by about 750 ha. There has also been a decrease of about 4,000 ha showing signs of minor sheet erosion and a corresponding increase of about 4,000 ha in the area that has no appreciable erosion.

Overall these statistics present a picture of a valley in which there has been a substantial increase in forest and tree cover (by about 25%) over the 25 year period. According to local landholders, the main reason for this has been the decline in the dairy industry. The reduction in the dairy industry has forced grazing activities to be confined to the more productive land that has left the more marginal land to revert to the original timber cover. Despite the encouraging trend in reduction of the area showing signs of erosion, there remains a large area (29,000 ha) showing signs of minor sheet erosion.

Despite the value of the mapping that has been undertaken for this study, it will not singularly provide data relating to the extent and type of forest cover at the time of European settlement.

3.4 Vegetation Communities

Land cover and land use analysis also examined vegetation classes in the catchment for the dates concerned. The distribution of vegetation communities across the valley were summarised in Table 3.3. The following procedures and definitions were adopted:

- Rainforest areas were derived from mapping undertaken by State Forests NSW.
- Wet sclerophyll forest was defined as mixed forest with visible understorey.
- Dry sclerophyll forest was defined as mixed forest with no visible understorey.

Among the noteworthy features represented in Table 3.3, there was a significant reduction in the area of ringbarked trees in 1991 compared to 1956. Of the 33,012ha reduction in ringbarked trees, 20,500 ha had reverted to scattered trees, 3,700 ha become areas of clumped trees, and 6,700 ha is now wet sclerophyll forest.

These changes in the vegetation cover are further evidence of the significant increase in tree cover that has occurred in the past 35 years. According to local landholders, the main reason for this has been the decline in the dairy industry. The reduction in the dairy industry has resulted in grazing activities being confined to the more productive land that was used for dairy farming, leaving the more marginal land to revert to forest cover.

Table 3.3: Vegetation classes in Nambucca catchment: 1956 and 1991

Vegetation Class	Area 1956 (ha)	Area 1991 (ha)	Difference 1991-56 (ha)
Dry sclerophyll forest	14,714	14,358	-356
Wet sclerophyll forest	49,856	56,577	6,721
Rainforest	1,551	1,543	-8
Swamp complex	218	262	44
No mature trees	4,533	6,113	1,580
Woodlot	560	1,328	768
Windbreak/Tree row	42	106	64
Scattered trees	11,142	31,602	20,460
Trees in clumps	2,255	5,935	3,680
Riverine natives	769	829	60
Ringbarked trees	33,866	854	-33,012
Urban — Residential	90	83	-7

3.5 Erosion

As part of the land use assessment, an aerial photo analysis of erosion on the catchment slopes was undertaken. The erosion status of the catchment is summarised in Table 3.4.

Table 3.4: Erosion classes in the Nambucca catchment: 1956 and 1991

Erosion Class	Area 1956 (ha)	Area 1991 (ha)	Difference 199 - 56 (ha)
No appreciable erosion	84,324	88,401	4,077
No erosion due to land use	1	14	13
Sheet erosion — minor	32,922	28,896	-4,026
Sheet erosion — moderate	30	107	77
Sheet erosion — severe	872	716	-156
Rill erosion — minor	5	77	72
Rill erosion — moderate	1,347	1,284	-63
Rill erosion — severe	2	9	7
Mass movement	5	4	-1
Urban - Residential	90	83	-7

The data in Table 3.4 indicates the same trend shown by the vegetation and land use data; namely a trend towards a catchment in better condition in 1991 than in 1956. The main trends have been a 4,000 ha decrease in land showing signs of minor sheet erosion and a corresponding increase of about 4,000 ha in the area that has no appreciable erosion. Despite this encouraging trend there remains a large area (29,000 ha) showing signs of minor sheet erosion.

3.6 Climate

As the western part of the valley is sparsely populated, climate datum is limited. Rain gauges occupy cleared sites in the valley floor and are not necessarily representative of the steep, forested slopes and high ridges. The Water Conservation and Irrigation Commission (now the Department of Land and Water Conservation) (1970) prepared a useful compendium of data that has been drawn upon here for some general climatic data. Much of the streamflow and rainfall data in that report has, however, been superseded by data collected in the ensuing 25 years. For this study, all available records have been obtained from the relevant agencies and analysed to show the patterns and trends.

3.6.1 Temperatures

Average daily temperatures vary with proximity to the coast. The minimum average daily temperature is about 5°C and the maximum about 30°C. The Bureau of Meteorology has no long-term climate stations in the Nambucca catchment. The nearest record of long-term climate data comes from Bellingen Post office, over the catchment boundary immediately north of Bowraville. The climate information can be seen in Figure 3.2.

Pan evaporation is estimated to vary from around 1,650 mm annually around Bowraville to about 1,200 mm in the upper catchment. Evaporation from open water will be about 0.8 of the pan evaporation rates (1,320 - 960 mm per year). Pan evaporation rates vary significantly throughout the year and at Bowraville, for example, ranges from 70 mm in July to 200 mm in January.

3.6.2 Rainfall Characteristics

Long term mean average annual rainfall over the estuary area of the basin is in the range 1,300 - 1,400 mm. In the northern and eastern part of the high ridge country it ranges between 1,300 -1,600 mm. To the west and south along Taylors Arm, the mean annual rainfall ranges from 1,600 mm in the western high areas to 1,200 mm in the south.

All official Bureau of Meteorology rainfall stations that lie within 50 km of Macksville were identified and the quality and duration of the available data were assessed. Daily rainfall data for about 30 of the best stations within and adjacent to the catchment were obtained for this study. These stations were used for an analysis of the distribution of rainfall across the catchment. Eight stations were identified as being suitable for detailed analysis of rainfall trends because of their location and the availability of long term unbroken records (Table 3.5).

Major influences on rainfall are the high ridges along the northern and southwest catchment divide. These ridges, which typically reach an elevation of 400 - 800 m, are sufficient to provide an orographic influence on the rainfall, particularly when a depression or the remnants of a cyclone creates on-shore winds.

Climatological Summary for BELLINGEN POST OFFICE — Site Number 59001

Latitude 30°27'12"S — Longitude: 152°53'50"E — Elevation: 15 Metres — Opened Jan 1899 — Still Open

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Years of Record
Mean Daily Maximum Temp (°C)	29.8	29.4	28.2	25.9	22.7	20.4	20.0	21.7	24.3	26.4	28.4	29.7	25.6	39
Highest Temperature (°C)	42.4	41.0	39.5	35.2	31.9	28.3	30.0	32.3	37.1	40.6	45.0	43.6	45.0	29
Lowest Maximum Temperature (°C)	19.9	19.4	18.2	15.5	15.0	12.2	12.5	13.3	15.0	13.6	15.0	17.8	12.2	29
Mean Number of days over 30°C	16.2	13.0	10.9	3.5	0.1	nil	nil	0.1	2.0	6.1	10.3	15.2	77.6	29
Mean Number of days over 35°C	3.6	2.2	0.5	nil	nil	nil	nil	nil	0.2	0.5	2.3	3.9	13.2	29
Mean Daily Minimum Temp (°C)	17.8	18.3	16.8	13.3	9.2	6.7	4.8	5.6	8.3	11.7	14.1	16.6	11.9	39
Lowest Temperature (°C)	11.1	10.7	8.3	3.8	-0.6	-1.7	-3.7	-3.3	-1.7	0.6	5.0	7.2	-3.7	29
Highest Minimum Temperature (°C)	24.0	24.4	22.3	22.0	19.4	16.1	18.9	15.6	18.9	21.0	25.6	24.3	25.6	29
Mean Number of Days below 2.2°C	nil	nil	nil	nil	1.2	3.9	9.6	5.5	0.8	0.1	nil	nil	21.0	29
Mean Number of Days below 0°C	nil	nil	nil	nil	0.2	0.7	2.8	0.9	nil	nil	nil	nil	4.6	29
Mean Daily Terrestrial Minimum (°C)														0
Lowest Daily Terrestrial Minimum (°C)														0
Number of Days Terrestrial below -0.9°C														0
Mean 9am Temperature (°C)	23.7	23.0	22.0	18.8	14.6	11.6	10.3	12.4	16.8	20.5	22.3	23.7	18.3	39
Mean 3pm Temperature (°C)	28.1	27.8	26.5	24.4	21.2	19.0	18.6	20.3	22.4	24.2	26.3	27.5	23.8	32
Mean 9am Relative Humidity (%)	74	80	80	81	84	86	83	76	68	64	65	67	76	30
Mean 3pm Relative Humidity (%)	65	66	68	64	62	62	55	51	53	57	56	60	60	23
Mean 9am Cloud Cover (oktas)	4.3	4.4	3.8	3.4	3.2	3.1	2.6	2.4	2.6	3.3	3.4	3.8	3.3	39
Mean 3pm Cloud Cover (oktas)	4.8	5.2	4.8	4.1	3.9	3.5	3.0	3.1	3.4	4.2	4.4	4.7	4.1	32
Maximum Wind Gust (km/h)														0
Mean Daily Wind Run (km)														0
Mean Number of Days of Strong Wind	0.2	0.4	0.1	0.2	0.3	0.4	0.5	0.6	0.6	0.4	0.2	0.3	4.3	29
Mean Number of Days of Gales	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	0.1	29
Mean Daily Pan Evaporation (mm)														0
Mean Daily Sunshine (hours)														0
Mean Number of Days with Hail	0.1	0.1	nil	nil	nil	nil	nil	nil	0.1	nil	0.1	0.2	0.6	29
Mean Number of Days with Snow	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	29
Mean Number of Days with Frost	nil	nil	nil	nil	0.9	3.4	8.0	4.4	0.6	0.1	nil	nil	17.4	29
Mean Number of Days with Fog	nil	0.1	0.1	nil	0.1	0.3	nil	0.1	nil	nil	nil	nil	0.9	29
Mean Number of Days with Thunder	1.6	1.3	1.0	0.6	0.3	0.1	0.1	0.2	0.7	1.2	2.1	2.8	12.0	29
Mean Number of Clear Days	8.0	6.3	8.8	11.2	12.5	13.3	16.5	16.8	15.0	11.5	9.9	8.9	138.7	30
Mean Number of Cloudy Days	13.4	13.4	12.5	10.3	9.9	8.6	7.4	6.7	6.8	10.2	10.7	12.0	121.8	30
Mean Monthly Rainfall (mm)	181.7	198.8	218.1	156.0	120.1	109.6	79.9	57.9	56.9	97.3	111.9	138.3	1526.6	102
Highest Monthly Rainfall (mm)	671.4	650.4	869.0	721.8	760.2	943.7	417.0	328.9	339.6	719.0	530.4	353.4	943.7	102
Lowest Monthly Rainfall (mm)	15.4	0.8	4.6	2.0	0.5	0.0	0.0	0.0	0.0	8.1	0.0	8.7	0.0	102
Mean number of Rain days	12.5	12.6	13.6	10.2	9.0	7.2	6.0	6.3	6.6	9.2	9.9	11.4	114.5	94
Highest number of Rain days	24	25	23	24	20	20	23	17	16	18	20	22	25	94
Lowest number of Rain days	5	1	1	1	1	0	0	0	0	1	0	3	0	94

Figure 3.2: Long-term climate record from Bellingen Post Office (1899-2001)

Table 3.5: Rainfall Stations Used for Analysis

Station Number	Station Name	Period of Record	Elevation (m AHD)
057016	New England National Park*	01/1936 - 11/1986	1,350
059000	Bellbrook*	01/1889 - to date	95
059002	Bowraville Post Office	01/1890 - to date	18
059016	Kalang*	01/1940 - 01/1974	10
059018	Macksville Country Club	01/1888 - to date	33
059024	Nambucca Heads Bowling Club	01/1904 - to date	5
059032	Taylors Arm	01/1949 - to date	80
059107	Girralong	01/1973 - to date	100

* located outside catchment

A disappointing feature of the available rainfall records from the Nambucca catchment is the paucity of rainfall record covering the period up to 1950. Apart from Nambucca Heads (since 1904), Macksville (since 1889) and Bowraville (since 1890), all lowland sites, the longest records in the non-tidal catchment are those from Thumb Creek (since 1961) and Eungai (since 1964). A number of different procedures have been used to analyse the data in order to assess climatic variation across the valley and the temporal variations which have occurred since records began, including an analysis of seasonal patterns and a residual mass curve analysis to illustrate long term rainfall trends (Figure 3.3).

Table 3.6 summarises the monthly average rainfall at the key stations analysed. It can be seen that February/March are usually the wettest months and August/September (late winter) the driest.

Table 3.6: Rainfall statistics from gauges within 50 km of Bowraville

Month	Average Monthly Rainfall (mm)							
	N/E Nat Park	Bellbrook	Bowraville	Kalang	Macksville	Nambucca Heads	Taylors Arm	Girralong
Jan	289	148	163	214	148	156	179	227
Feb	283	159	179	236	165	176	184	232
Mar	339	153	185	215	176	192	173	211
Apr	201	96	130	116	130	157	121	185
May	149	74	102	77	109	120	90	125
Jun	164	79	106	112	103	105	96	84
Jul	99	56	68	81	68	71	50	67
Aug	114	49	55	80	34	64	56	31
Sept	76	47	56	52	30	61	45	45
Oct	135	74	85	94	84	84	84	92
Nov	148	90	95	103	91	96	97	139
Dec	224	122	124	151	123	120	126	173
Av. Annual	2,221	1,148	1,350	1,530	1,321	1,402	1,300	1,544
Av Monthly	184	95	112	128	110	117	109	135

3.6.3 Rainfall Distribution Across the Catchment

Rainfall distribution across the catchment for various time periods was assessed by the preparation of isohyet maps, based on average annual rainfall (Figure 3.4). From the trends in rainfall at Bowraville, three periods have been chosen for analysis;

- 1900 -1919 (a drier than average period)
- 1920 - 1949 (an average period)
- 1950 - 1990 (a wetter than average period)

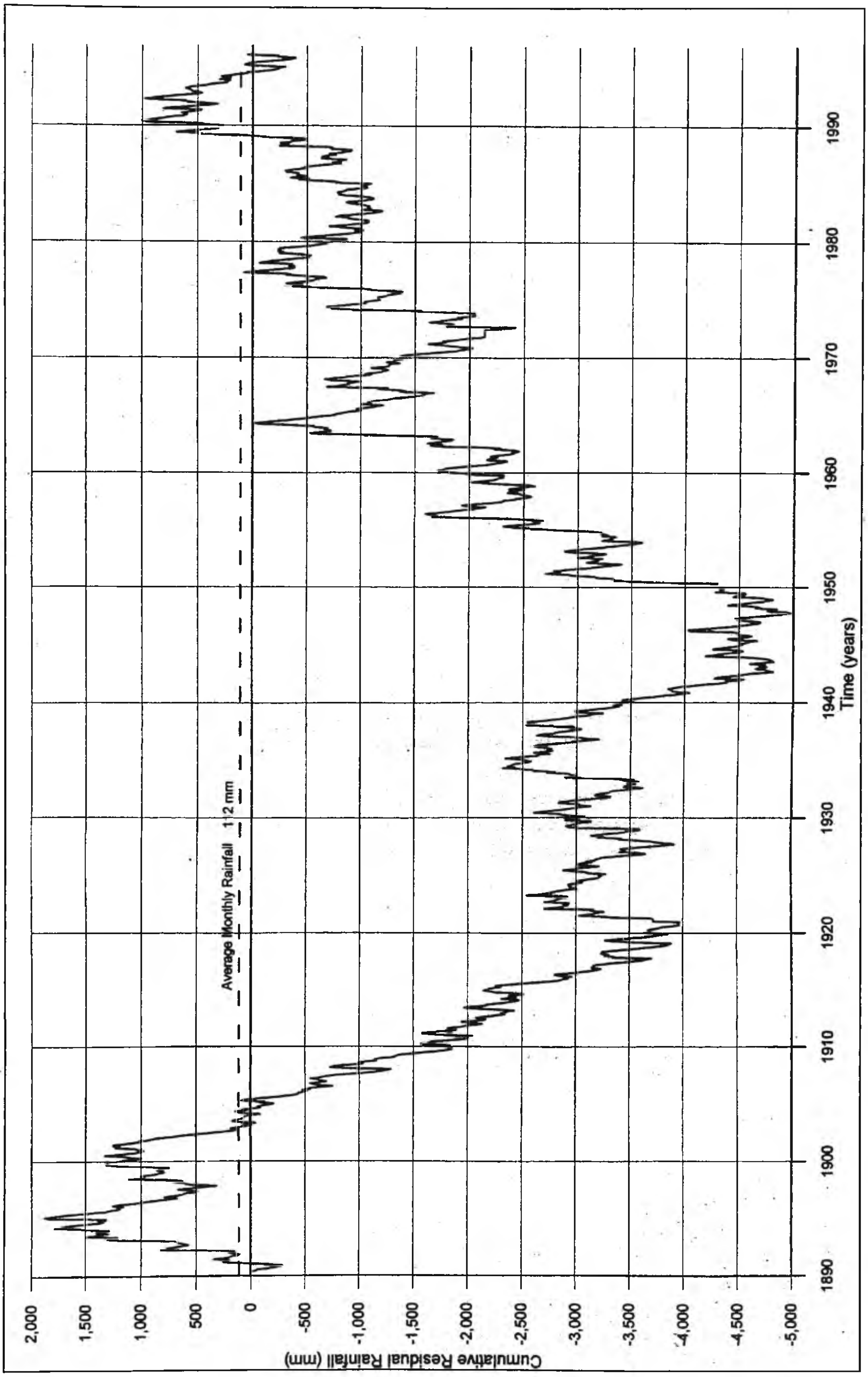


Figure 3.3: Rainfall residual mass curve for Bowraville Post Office (059002)

Table 3.7 summarises some of the differences in average annual rainfall for these periods at different locations. For the drier period (1900 - 1919) there is a rainfall gradient from about 1,200 mm/year in the northeast to about 1,000 mm/year along the southwestern boundary of the Taylors Arm catchment. For the average rainfall period (1920 - 1949) the northeast to southwest trend has a superimposed pattern associated with the orographic effects of the higher elevations around Killiecrankie Mountain. For these years, the average annual rainfall throughout the catchment is significantly higher than for the drier period and varies from about 1,350 mm/year over Deep Creek and about 1,200 mm on the headwaters of Warrell Creek to about 1,700 mm/year at Killiecrankie Mountain.

The wetter period (1950 - 1990) shows a similar pattern to the average period except that the rainfall over the lower parts of the catchment is higher by more than 100 mm/year and is increased at Killiecrankie Mountain by about 50 mm/year. The Deep Creek catchment received about 1,500 mm/year over this period while the Warrell Creek catchment divide received about 1,300 mm/year.

Table 3.7: Average annual rainfall variation across the Nambucca catchment for dry, average and wet Periods

Location	**Dry (1900 - 1919)** (mm/year)	**Average (1920 - 1949)** (mm/year)	**Wet (1950 - 1990)** (mm/year)
Deep Creek: north-eastern boundary	1,200	1,370	1,500
Killiecrankie Mountain	1,050	1,700	1,750
Bowraville	1,100	1,300	1,450
Taylors Arm	1,000	1,250	1,350
Warrell Creek: south-western boundary	970	1,200	1,270

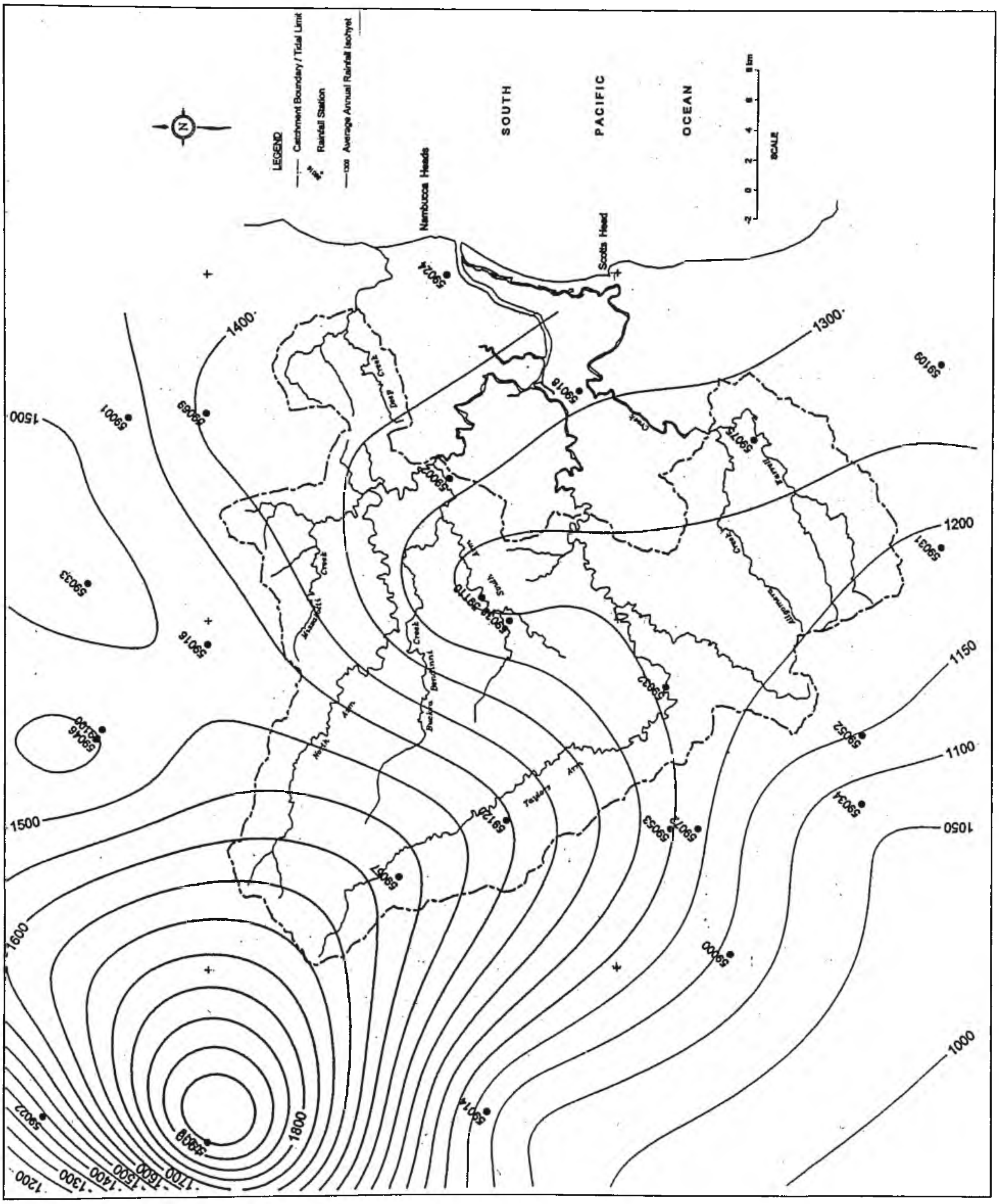


Figure 3.4: Isohyet map of average annual rainfall in the Nambucca catchment (1890-1995)

3.6.4 Rainfall Trends

A number of distinct trends over time are summarised in Table 3.8. The major trends found were:

- From about 1895 to 1920 rainfall was less than the averages obtained for the following two periods.
- The period from about 1920 to 1940 rainfall was above average.
- From 1940 to 1950 rainfall was again less than average.
- 1950 to 1965 was a period of more than the average rainfall (graph slopes upwards to the right).
- The period 1965 to about 1973 was again drier than average.
- 1973 to about 1977 was a period of above average rainfall.
- This was followed by a dry period up to about 1983, a short wetter period to 1990 and a drier period since 1990.

Table 3.8: Rainfall trends

Dry Periods	Average Periods	Wet Periods
1895 — 1920	1920 — 1940	1890 - 1895
1940 — 1945	1945 — 1950	1950 - 1965
1965 — 1973	1982 — 1988	1973 - 1978
1978 — 1982		1989 - 1992
1992 — 1996		

Residual mass curves for other stations in and adjacent to the Nambucca catchment show similar patterns to those shown at Bowraville. The main conclusion to be drawn from this analysis of rainfall trends is that since European settlement there have been several different rainfall epochs. In terms of the changes that have occurred in the Nambucca catchment the most notable periods have been from 1895 to 1949, which had below average or average rainfall over a period when much of the clearing of lower slopes for grazing occurred, and the early 1950's were particularly wet as were the early 1960's and the mid 1970's. Anecdotal evidence indicates that the early 1950's and the mid 1970's, in particular, were associated with major destabilisation of the river systems.

It must also be noted, however, that the significant variations in rainfall over the period since European settlement will have led to changes in the flow regimes of the rivers. This climatic variation will tend to hide any variation in streamflow regime that might be attributable to changes in land use.

3.7 Streamflow and Hydrology

3.7.1 River Gradients

Bed gradients on the river systems have been determined both by measurements from contour intervals on 1:25,000 maps and from limited topographic survey data up and downstream of a number of cross sections on the Nambucca River and Missabotti Creek undertaken by the Department of Land and Water Conservation in 1996. Comparison of these two sources showed close agreement and gave confidence that map slopes were appropriate for purposes of assessing the broad hydraulic characteristics of the river systems.

Table 3.9 summarises the variation in riverbed gradient for three sections of each catchment. As might be expected the channels have very steep gradients (14 - 16%) in the headwaters of Taylors Arm, the Nambucca River and Buckra Bendinni with, Missabotti Creek and South Arm showing lower gradients in the headwaters (about 6%). Both Warrell Creek and Deep Creek show much flatter gradients in the headwaters (2 - 3%) than the larger river systems that rise in the steeper hills further west. In all cases bed gradients fall rapidly from the upper catchment and reach values in the range of 0.1 - 0.2% where the rivers join or near their tidal limits.

Table 3.9: River gradients in the Nambucca catchment

Sub-catchment	Bed Slope (%)		
	Upper Catchment	Upper - Middle Catchment	Lower Catchment
Missabotti Creek	6.3%	1.2%	0.15%
Buckra Bendinni Creek	14.3%	0.8%	0.08%
South Arm	5.9%	1.4%	0.18%
Nambucca River	16.7%	1.0%	0.14%

Taylors Arm	14.3%	0.3%	0.12%
Warrell Creek	1.7%	0.4%	0.14%
Deep Creek	3.3%	1.0%	0.20%

3.7.2 Stream Gauge Data

The long-term stream gauging stations (with the periods of record for which continuous daily records are available) for the Nambucca catchment and adjacent rivers is shown in Table 3.10.

Table 3.10: Stream gauging station records

Station Number	Station Name	Period of Record	Catchment Area (km^2)
205002	Bellinger River @ Thora*	02/1982 - to date	433
205006	Nambucca River @ Bowraville	08/1971 - to date	430
205008	Taylors Arm @ Grays Crossing	03/1970 - 01/1989	340
205009	Warrell Creek @ Warrell Creek	05/1980 - 10/1985	200
206011	Macleay River @ Turners Flat*	01/1970 - to date	9,980

* Not in Nambucca catchment

Unfortunately, these records cannot be used to define the flow regime in local rivers prior to 1949/50 when major changes occurred. Nevertheless, these records have been obtained for detailed analysis to look at correlations between stations and to interpret flood frequencies relevant to the geomorphological behaviour of the rivers.

A substantial analysis of the recent flood history of the Nambucca was carried out for the Lower Nambucca Flood Study (PWD, 1994) providing a useful foundation for further detailed analysis of longer-term flood history to take account of unofficial records prior to the establishment of a formal stream gauging station at Bowraville. This data has been used to look at the pattern of flooding over the years as well as the relative magnitude of significant flood events.

Additional analysis was undertaken including a study of floods of geomorphological importance that occur in the range of once every three months to once in two years. The

flow record was also used to identify any long-term trends. The daily records were cumulated to yearly figures and both sets were analysed to determine the mean, median, minimum and maximum annual flows. These statistics are summarised in Table 3.11. The most pertinent aspects of the data presented in Table 3.11 include the similarity in the average annual catchment yields for the Nambucca River (477 mm) and Bellinger River (462 mm). Warrell Creek and Taylors Arm have the same average annual catchment yields (366 mm), which is significantly less than the Nambucca or Bellinger rivers.

Table 3.11: Streamflow summary statistics

	Bellinger River @ Thora		Nambucca River @ Bowraville		Taylors Arm @ Grays Crossing		Warrell Creek @ Warrell Creek	
	ML	ML/km^2	ML	ML/km^2	ML	ML/km^2	ML	ML/km^2
Daily Flow								
Avg	590	1.36	560	1.30	360	1.06	185	0.93
Median	190	0.44	25	0.05	50	0.15	15	0.08
Min	5	0.01	0	0	1	0	0	0
Max	62,180	145	111,040	260	61,080	180	16,975	85
Annual Flow								
Avg	200,170	460	205,320	475	124,470	365	73,310	365
Median	186,330	430	126,530	295	95,170	280	52,670	265
Min	17,820	40	7,830	20	9,600	30	50,600	255
Max	425,560	980	741,510	1,725	400,370	1,175	120,300	600
Average Annual Runoff								
(mm)^A	462		477		366		366	
(%)^B	29%		32%		25%		27%	
Daily Flow								
Peak ^{C}	31%		54%		49%		23%	
Min ^{D}	0.8%		0%		0.3%		0%	

A = Average annual runoff expressed as a depth of runoff over the whole catchment.
B = Average annual runoff expressed as a percentage of average annual rainfall.
C = Peak daily flow as a percentage of average annual flow
D = Minimum daily flow as a percentage of average daily flow

In terms of the percentage of average annual rainfall which appears as runoff, the Nambucca River (32%) is slightly higher than the Bellinger River (29%), Warrell Creek (27%) and Taylors Arm (25%). (The Macleay River, which has a catchment of 10,000 km^2 - about 25 times the size of the Nambucca, has an average annual runoff of about 15% of rainfall). It is surprising to note that, despite having a slightly higher average annual rainfall, Taylors Arm (25%) has a lower percentage average annual runoff than Warrell Creek (27%). The explanation for this apparent anomaly might be the relatively short record at Warrell Creek (1980 - 1985) compared to the longer record for Taylors Arm (1970 - 1989). The Nambucca River appears to have the most variability in streamflow with a maximum observed daily flow equal to 54% of the average annual flow. In descending order of variability the other rivers are: Taylors Arm (49%), Bellinger (31%) and Warrell Creek (23%).

3.7.3 Flood Frequency

Previous analysis of the hydrology of the Nambucca catchment was carried out by Willing and Partners for the Department of Public Works and Services and presented in the Lower Nambucca Flood Study (PWD, 1994). The study was prepared for Nambucca Council to define flood behaviour under current conditions, and to define the nature and extent of the flood hazard for the 1%, 2% and 5% Annual Exceedance Probability (AEP) floods. The study area comprised the river and associated floodplains from the mouth of the Nambucca River upstream to Wirrimbi Island, Congarinni Bridge and the Pacific Highway Bridge.

The analysis for this study is based on a partial series (flows exceeding a certain value) rather than the annual series (highest flows for each year for the period of record) for the periods of record shown in Table 3.12. It can be seen that a different period of record has been used for the two studies. For these reasons, the flows obtained in the flood frequency and flow duration analyses will be different to those presented in the Nambucca Flood Study Report (PWD, 1994).

Table 3.12: Stream gauging station records

Station Number	Station Name	Period of Record for Analysis	
		Flood Study	Current Study
205006	Nambucca River at Bowraville	1959 - 1986	1971 - 1996
205008	Taylors Arm at Grays Crossing	1970 - 1987	1970 - 1989
205009	Warrell Creek at Warrell Creek	1971 - 1983	1980 - 1985

Flood frequency analysis was carried out for the Bellinger River as well as the three stations within the valley, based on the daily data supplied by DLWC and augmented with additional historic flows from the Nambucca Flood Study Report (PWD, 1994) and the Nambucca Flood History report compiled by PWD (1980). The analysis was carried out according to the method outlined in Australian Rainfall and Runoff (1987). A summary of the resulting flood flow estimates for various probabilities of occurrence (expressed in terms of AEP) are summarised in Table 3.13.

Table 3.13: Estimated peak flood discharges (m^3/s)

AEP (%)	Bellinger	Nambucca	Taylors Arm	Warrell Ck
20	710	1,050	570	280
5	1,480	2,230	1,030	410
2	2,080	2,960	1,280	460
1	2,580	3,440	1,440	510

The peak discharge estimates shown in Table 3.13, especially those for Nambucca River at Bowraville (205006), are significantly higher than those presented in the Flood Study (PWD, 1994). This is partly due to the fact that there were nine years of additional data available to carry out the analysis and also due to this analysis using the partial series.

3.7.4 Discharge Trends

Correlation between the data sets for major gauging stations indicate that there are no major divergences between stations that would indicate changes in the flow regime of one of the catchments. Unfortunately the period of record available for analysis is

relatively short and corresponds with periods in which there have been considerable fluctuations in the rainfall trends. The double mass curve analysis does not, therefore, provide useful evidence of changes in the hydrologic regime of the catchments examined.

A residual mass curve was produced for the Nambucca River at Bowraville. The curve showed the same trends reflected in graphs for the other stations and also reflects the pattern of the rainfall residual mass curve for the same period (Figure 3.5).

3.7.5 Low and High Flows

For the purpose of this analysis, low flows were defined as those below the 10th percentile (low) flow, while high flows were defined as those above the 90th percentile (high) flow. The high flows were analysed to determine the frequency of days of high flow for each month. The results for various stations are summarised in Table 3.14.

Table 3.14: Occurrence of high flows by month

Month	Occurrence of Flows Greater than 90 Percentile Flow (% of time)			
	Bellinger (1,149 ML/d)	Nambucca (1,344 ML/d)	Taylors Arm (567 ML/d)	Warrell Creek (186 ML/d)
January	16%	15%	18%	9%
February	17%	15%	14%	13%
March	26%	21%	22%	15%
April	17%	20%	14%	16%
May	7%	8%	10%	19%
June	5%	6%	5%	9%
July	2%	4%	4%	5%
August	1%	0%	1%	0%
September	0%	0%	1%	0%
October	2%	4%	4%	3%
November	2%	3%	4%	5%
December	6%	4%	5%	7%

With the exception of Warrell Creek, it can be seen that high flows occur most frequently in the period January to April with the highest flows in March. For Warrell Creek, May has the greatest percentage of days of high flow. In general, high flows occur infrequently in September and August.

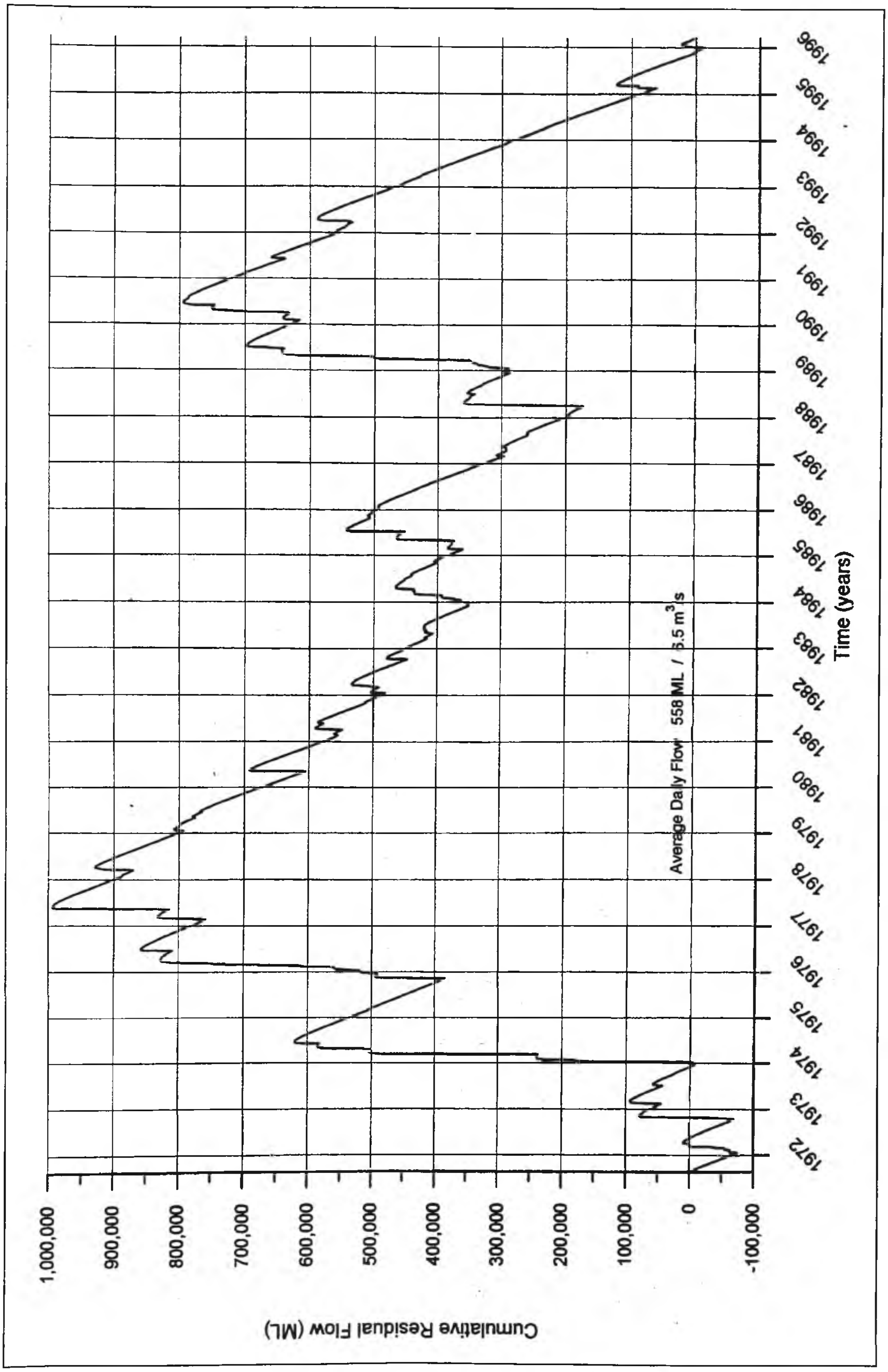


Figure 3.5: Flow residual mass curve for the Nambucca River at Bowraville (205006)

An assessment of low flows commenced by identifying flows less than the 10th percentile daily flow. The occurrence of these flows as a function of month was determined, as well as the number of days the low flows persisted. The results are presented in Table 3.15 below.

Table 3.15 indicates that low flows occur most frequently between September and December and least frequently in the period March to June. The average duration for episodes of low flow is around 2 to 4 weeks, depending on the catchment. However, a low flow episode 6 months long was experienced from July 1994 - January 1995 at the Bowraville gauge. A five-month low flow episode was experienced from September to December 1970 at the Taylors Arm gauge.

Table 3.15: Occurrence of low flows by month

Month	**Occurrence of Flows Less Than the 10 Percentile Flow (% of time)**			
	205002 (46 ML/d)	**205006 (18 ML/d)**	**205008 (9 ML/d)**	**205009 (2 ML/d)**
January	11%	7%	13%	0%
February	3%	0%	13%	11%
March	0%	5%	0%	22%
April	0%	1%	4%	0%
May	0%	2%	0%	0%
June	0%	2%	4%	0%
July	3%	7%	4%	0%
August	17%	5%	0%	0%
September	11%	12%	17%	33%
October	20%	17%	22%	22%
November	23%	12%	0%	0%
December	11%	20%	22%	11%
Persistence of Low Flows (days)				
Average	14	22	29	22
Range	1 - 75	2 - 182	2 - 135	2 - 81

3.7.6 Major Floods

The main gauge at Bowraville has recorded flood heights extending back to the 1880's (PWD, 1994). All major floods at Bowraville are recorded as those over 8.0 m AHD. Table 3.16 indicates that there have been 29 floods over 8.0 m. Of these there have been only 7 floods in the past 115 years that have exceeded 10.0 m.

Table 3.16 Floods recorded at Bowraville over 8.0 m AHD

Date	Height (metres above AHD) @ Lane's Bridge Bowraville
1890 January	9.50
1890 February	10.40
1890 March	11.90
1893 February	10.40
1894 March	8.90
1913 May	8.90
1921 May	9.20
1921 July	9.50
1929 February	8.90
1948 January	8.60
1948 October	9.80
1949 August	9.80
1950 June	10.90
1953 March	9.10
1954 February	11.00
1959 November	9.50
1962 April	9.70
1963 April	8.90
1963 May	9.70
1964 March	9.50
1967 June	8.90
1968 January	9.10
1972 October	9.50
1974 March	10.70
1977 May	10.00
1989 July	9.30
1990 May	8.10
1997 June	8.20
2001 January	8.10
2001 March	8.60

3.8 Hydrologic Effects of Land Use Change

3.8.1 *Introduction*

One of the issues that needs to be examined in the Nambucca catchment is whether there has been any significant change in the hydrologic regime as a result of changes in land use and land management since European settlement. It has been recognised for many decades that one of the most profound effects of European settlement in Australia has been the impact of cleaning of native forest on the hydrologic regime (Warner, 1992). Throughout Australia there are numerous documented cases of increased recharge to the groundwater and changes in surface runoff and sediment movement as a result of clearing native forest (eg. Haworth, 1994). The type and magnitude of hydrological changes that occur is dependent on the climate of the area and the hydrologic processes at work. In forested hill country, the immediate impact of forest clearing or an intense bushfire is a short-term (1-4 year) increase in catchment yield. This is often followed by a long period (30+ years) of reduced yield attributable to the increased transpiration of the regrowth forest. Where groundwater processes are important, the impact of forest clearing may take several decades to become apparent and its effects often go unnoticed until groundwater levels have risen sufficiently to cause increased seepage into drainage lines.

The question of the hydrologic effects of land use change has been of considerable interest to Australian hydrologists and has been the subject of extensive studies over many decades. A number of extensive reviews have been prepared over the years. Some of the keys ones are Boughton (1970), Flemming et al. (1991) and Bonell (1993).

3.8.2 *Possible Hydrologic Change in the Nambucca Catchment*

As has been noted earlier, any evidence of hydrologic changes in the Nambucca catchment will be hard to find because detailed hydrological records commence after any major changes are likely to have occurred. Even if records were available there remains the difficulty of knowing whether an observed change is statistically significant and what has caused it. This difficulty is well illustrated by a study conducted by Langford and Lewis (1975) who examined various statistical tests for detecting hydrologic change. Their study used data from a number of catchments near Melbourne that had shown a change in the hydrologic response as a result of intense bushfires. Following

regeneration of the Mountain Ash forest the catchments showed a reduction in water yield of 13 - 31%, which were apparent even 40-60 years after the fire. Their analysis showed that a change of the order of 20 % of the mean is required before the significance of a change can be established.

In assessing any evidence for hydrologic change in the Nambucca catchment there are several factors and pieces of evidence that must be taken into account in assessing both the climatic and hydrologic record. For instance, rainfall varies significantly across the valley and different catchments receive different amounts of rainfall and can be expected to show slightly different behaviour.

There has been several rainfall epochs since records began. These epochs have lasted for between one and three decades each. In drier periods, average annual rainfall has been about 10% less than the long-term average and in wetter periods it has been about 10% higher. These separate sub-catchments in the Nambucca catchment (Nambucca River, Taylors Arm and Warrell Creek) exhibit significant differences in hydrologic behaviour that is summarised in some simple statistics in Table 3.17. These differences, particularly the differences in the flood regime, mean that there would be difficulties in detecting any changes in land use in one particular catchment and not another.

Table 3.17: Comparative runoff and flood flow characteristics of tributary catchments in the Nambucca

River	Average Annual Discharge (ML/km^2)	Average Annual Runoff (% of rain)	Average Annual Flood ($m^3/s/km^2$)
Nambucca	477	32%	1.12
Taylors Arm	366	25%	0.93
Warrell Creek	366	27%	0.75

The limited period of common record indicates that there have been no significant shifts in the relative runoff characteristics of the three catchments. This is hardly surprising, but does serve to illustrate some of the difficulties that are involved in detecting any hydrologic change.

The flood record at Bowraville provides some evidence that there has been no significant hydrologic change since European settlement. The record shows that the largest flood on record occurred in 1890 and that this flood appears to be drawn from the same statistical population as those that have occurred since. The flood of 1890 is interesting in another respect. Whilst it is the largest flood on record at Bowraville, there are no records of large-scale change having occurred in the rivers as a result of that flood, whereas the floods of 1949 and 1950, which were smaller floods than the 1896 flood, are reported to have led to widespread changes to the river channels.

3.8.3 Hydrologic Effects of Forest Clearing in Eastern Australia

One of the major changes that have occurred in Australia in the period of European settlement is that large areas of native forest have been cleared for conversion to pasture or crops. There has been a lot of interest in this topic, particularly in southeastern and southwestern Australia where research studies have been undertaken over the past 30 years. On the east coast, the major centres where studies of catchment hydrology have been undertaken including catchments surrounding Melbourne, Eden on the NSW south coast, Karuah in the Hunter valley area, Babinda in north Queensland, and the north west slopes of NSW (Lyall and Macoun, 1997). Unfortunately none of these areas have exactly the same climatic conditions as those experienced in the Nambucca area. In particular there are significant differences in the major climatic influences that affect the hydrologic response, with dominant rainfall of low intensity in the Melbourne and Eden areas and summer dominant high intensity rainfall in the wet tropics at Babinda. These differences in climate will be reflected in differences in the hydrologic processes at work and will therefore influence the response of a catchment to changes in vegetation cover (Brierley et al., 1999).

A further factor that must be considered in assessing the relevance of any measured changes in hydrologic response to catchment manipulation is that of scale (Schumm, 1969). Most catchment experiments involving forest clearing have occurred on relatively small catchments (less than 100 ha). In these catchments the runoff generation processes occurring at or near the land surface will govern the peak flow rate. This contrasts with larger catchments (100 km^2 or more) where the peak rate of runoff will be determined largely by the hydraulic conveyance and storage characteristics of the river system.

Where deep rooting trees have been replaced by shallow rooting grasses, an increase in the total amount of runoff from the catchment usually results. In general, when forest cover is removed there is an initial increase in water yield that is related to the proportion of cover affected (Hibbert, 1967). If the forest is allowed to regenerate and grow, catchment yield then declines in a manner dictated by increases in the transpiration rate and rainfall interception rate of the regenerating forest. Changes in these fundamental components of forest evapotranspiration result largely from increases in leaf area of the regrowth stand (Swift et al., 1988).

3.8.4 Groundwater

There are numerous studies of the effects of removal of vegetation cover on the groundwater regime in Australia. Most of these studies relate to inland plains or areas where groundwater processes are important (eg. south west Western Australia). The significance of these studies for the Nambucca is because they show that the groundwater regime reacts more slowly than surface runoff systems, it can take many decades for changes in the groundwater regime to become apparent.

An example of groundwater rise resulting from clearing of vegetation in the Callide Valley in Queensland has been documented by Melzer (1962) (quoted in Boughton 1970). Most of the Callide area was originally covered by forest and dense scrub. From 1924 onwards, a large amount of clearing and ringbarking of the scrub and forest followed by burning was carried out. Between 1953 and 1956, clearing of the vegetation was accelerated by aerial spraying and further accelerated between 1954 and 1961 by the use of heavy earthmoving machinery. Vegetation maps of the area in 1921, 1945 and 1961 document the progressive clearing and records of groundwater levels in the area show subsequent rises where clearing occurred. Rises of up to 10 m in groundwater level were recorded. Melzer (1962) concluded that the rises in groundwater level were directly attributable to clearing, and that the denser the vegetation prior to clearing the higher the water table rises after clearing.

In South Australia, Holmes and Colville (1968) described the different rates of groundwater recharge occurring under forest and grassland areas in the Gambier Plain. Rainfall and soil moisture storage measured at two sites in pine forest showed no groundwater recharge occurring. In comparison, studies of the water budget of grassland showed an average recharge to groundwater of about 85 mm/year.

Sharma et al. (1982) reported on detailed studies of two adjacent catchments near Collie in Western Australia over a period of eight years. These studies were undertaken to evaluate the effect of clearing of native forest. The study found that the change in land use induced a significant increase in soil water storage and a rise in groundwater level, and resulted in substantially increased export of salts and water from the catchment. Increase in soil water storage was pronounced during summer particularly at depths below 1 m and the groundwater level rose by 1.3 m in the cleared catchment leading to the development of perennial seepage areas. In the forested catchment there was evidence of water extraction by trees down to 6 m, which caused the water table to be lowered by 0.25 m. Their study showed that a major cause of the increased groundwater recharge was that the grass and agricultural crops only extracted moisture from the top 2 m of soil, at most, while the forest trees extracted deeper soil moisture before it reached the watertable.

In South Australia, Allison (1975) examined groundwater recharge on the Gambier plain using the tritium concentration of rainfall as an indicator of water movement. The area has an average annual rainfall of 700-750 mm and is hydrologically unusual in that little surface drainage has developed. Allison found that recharge of between 50 and 180 mm per year occurred under pastures. Beneath native forest the recharge was found to be about 30 mm per year.

4. FLUVIAL GEOMORPHOLOGY OF THE NAMBUCCA CATCHMENT

4.1 Introduction

This chapter describes the contemporary fluvial geomorphology of the Nambucca catchment, providing details of the character of study reaches along each of seven main tributaries. It interprets data on channel cross-sections, planforms, a range of calculated discharges, bankfull stream-power, channel incision, channel and valley gradients, floodplain stratigraphy, bank erosion and bank strength, and it presents a selection of floodplain chronologies. This data was used to assess the fluvial history and present conditions in the catchment in order to interpret the extent and severity of the environmental changes that have occurred since European settlement. These interpretations are used to appraise appropriate river management practices for the Nambucca catchment outlined in Chapter 8.

The streams of the catchment were examined in detail at 36 study sites located below each major tributary junction. Viewed downstream, these reaches illustrate channel variables responding to the accumulative effects of changing flow discharge and variations in other parameters including channel and valley gradients, channel sinuosity, sediment texture, channel roughness, bank strength, valley width and floodplain character. Pictorial examples outlining the methodologies of the geomorphic information collection in the field can be seen in Appendix 4.

4.2 Geomorphic Indices

Valley slopes, channel slopes and planform sinuosities were measured from 1:25,000 maps and aerial photographs. These statistics were collected for each tributary in its entirety. Additionally, reaches were selected along each tributary that were known to be stable or unstable and the same parameters were recorded. This information may assist in establishing cause or effect for relative states of channel stability. After the above information was obtained for each catchment, data was then estimated, measured and calculated for each individual study site where a section was surveyed across the channel and adjacent floodplain. This data included; bankfull width, valley width, bankfull discharge, stream power, estimated Manning's n, annual peak-discharge and estimated stable width.

4.3 Methods for Obtaining Geomorphic Information

4.3.1 Field Sites

The seven streams chosen for detailed sediment analysis were Taylors Arm, North Arm, Missabotti Creek, South Arm, Buckra Bendinni Creek, Deep Creek and Warrell Creek. On each stream, sites were chosen because they were downstream of a major tributary or, should there be no major tributary, because they were a substantial distance (~10 km) from the previous site. Each site was located on a riffle in a straight reach because riffles were readily accessible at low flow. The complete list of sites is given in Table 4.1 and the location of these sites can be seen in Figure 4.1.

Table 4.1: Name and Abbreviation of Field Sites

SITE	ABBREVIATION
Taylors Arm Site 1	T1
Taylors Arm Site 2	T2
Taylors Arm Site 3	T3
Taylors Arm Site 4	T4
Taylors Arm Site 5	T5
Taylors Arm Site 6	T6
Taylors Arm Site 7	T7
Taylors Arm Site 8	T8
Taylors Arm Site 9	T9
Taylors Arm Site 10	T10
Taylors Arm Site 11	T11
North Arm Site 1	N1
North Arm Site 2	N2
North Arm Site 3	N3
North Arm Site 4	N4
North Arm Site 5	N5
North Arm Site 6	N6
North Arm Site 7	N7
Missabotti Creek Site 1	M1
Missabotti Creek Site 2	M2
Missabotti Creek Site 3	M3
Missabotti Creek Site 4	M4
South Arm Site 1	S1
South Arm Site 2	S2
South Arm Site 3	S3
South Arm Site 4	S4
South Arm Site 5	S5
Buckra Bendinni Creek Site 1	B1
Buckra Bendinni Creek Site 2	B2
Buckra Bendinni Creek Site 3	B3
Deep Creek Site 1	D1
Deep Creek Site 2	D2
Deep Creek Site 3	D3
Warrell Creek Site 1	W1
Warrell Creek Site 2	W2
Warrell Creek Site 3	W3

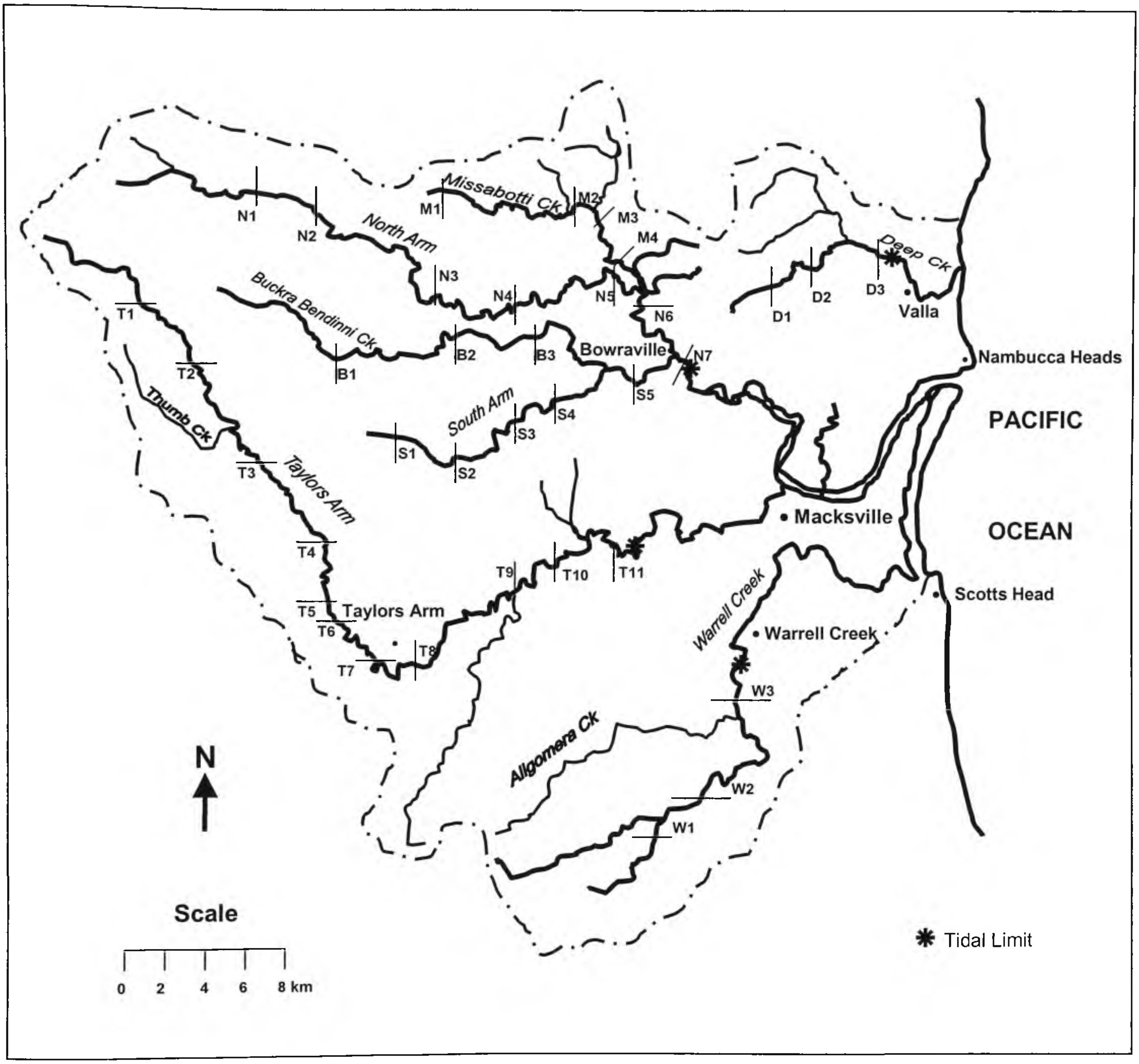


Figure 4.1: Location of field sites and cross sections in the Nambucca River catchment

4.3.2 *Indices for Collective Reaches*

Valley slopes, channel slopes and planform sinuosities were measured from maps and aerial photographs. These statistics were collected for each tributary in its entirety. Additionally, reaches were selected along each tributary that were known to be stable or unstable and the same parameters were recorded. This information may assist in establishing cause or effect for relative states of channel stability (Tables 4.2 to 4.8).

4.3.2.1 Valley Slope

Valley slope is largely an inherited characteristic that plays an important role in determining the rate of energy loss along a river (Knighton, 1988). Here it was measured along the centre-line of a valley from 1:25,000 map sheets.

4.3.2.2 Floodplain Width

Is the total width across the channel and flanking floodplains between the valley sides or terraces. This was surveyed at each of the 36 study sites.

4.3.2.3 Stream Slope (Gradient)

Is related to but usually less than the valley slope because the channel follows a wandering path rather than the centre-line of the valley. It was measured from 1:25,000 map sheets and checked in several locations by field surveys. For eight sites on Taylors Arm stream gradients were measured by surveying approximately 1 km of long profile. These initial eight field measurements provided comparable results (within 15%) of the slopes derived from 1:25,000 maps. By undertaking long profile surveying at eight shallow (and therefore readily accessible) reaches the author was able to use gradients derived from 1:25,000 map contours for the remaining sites in the catchment with confidence.

4.3.2.4 Sinuosity

Represents the irregularity of the channel planform and is expressed for an individual reach as the ratio of channel (*thalweg*) length to valley length. It ranges from 1.0 for perfectly straight channels to around 3.0 for highly tortuous channels. Channels with

sinuosities >1.5 are generally described as meandering. Channel and valley distances are measured from recent aerial photographs.

4.3.3 *Indices for Individual Sites*

After reach information was obtained for each tributary, data was then estimated, measured and calculated for each individual study site where a section was surveyed across the channel and adjacent floodplain. This data included; bankfull width, valley width, bankfull discharge, stream power, estimated Manning's n, annual peak-discharge and estimated stable width (Table 4.9). The terms are described below:

4.3.3.1 Bankfull Width

This is the distance apart from opposing stream banks when the channel is full (just before floodwaters spill onto the floodplain) and was surveyed in the field along with channel cross sections.

4.3.3.2 Calculated Width

Richards (1976) formulated an empirical equation to estimate bankfull stream width for a stable stream with pools and riffles.

Riffles: $W = 4.54\ Q_{bf}^{0.33}$

Pools: $W = 3.85\ Q_{bf}^{0.35}$

where Q_{bf} is discharge at bankfull.

As the cross-sections in this study were predominantly surveyed out on riffles, the first equation was used with Q_{bf} being the bankfull discharge as estimated using the Manning equation.

4.3.3.3 Manning's Q_b

Manning's equation ($Q = 1/n.\ A.R^{2/3}\ S^{1/2}$) was used to calculate bankfull discharge (where n = Manning's roughness co-efficient; A = cross sectional area; R = hydraulic radius; and S = slope).

4.3.3.4 HEC-RAS Q_b

Bankfull discharges were also calculated using the HEC-RAS program. HEC-RAS is a Windows-based computer program developed by the U.S. Army Corps of Engineers (1998). HEC-RAS incorporates several aspects of hydraulic modeling, including water surface profile computations, one-dimensional steady flow, and unsteady flow simulation. For this study surveyed channel cross sections were used to calculate bankfull area and slopeswere derived from field surveys and map estimates.

4.3.3.5 HEC-RAS Q_m

Mean annual flood discharge derived from the HEC-RAS model.

4.3.3.6 Gross Stream Power Ω

Available stream power or rate of doing work per unit of channel length where $\Omega = \gamma QS$ (γ = specific weight of water: Q = Discharge; S = Slope). This is a measure of the total energy available within the cross-section.

4.3.3.7 Specific Stream Power ω

Power per unit of width (a factor closely related to shear stress but including flow velocity) where $\omega = \Omega/W$ (W is width).

4.3.3.8 Manning's n

The Manning roughness co-efficient is an estimate of total flow roughness at a cross section. As flow rises the value of n can change as the relationship between the flow and the resisting boundary changes, and as spill resistance increases. The more heavily vegetated the channel, the higher Manning's n. It cannot be directly measured and was estimated here from comparative illustrations of locations in the USA and New Zealand where roughness has been calculated from the Manning's equation from known discharge, depth and slope measurements (Barnes 1987).

4.3.4 Geomorphic Information

Tables 4.2 to 4.8 display the reach characteristics for each tributary. This information was obtained from topographic maps and aerial photographs.

Table 4.2: Reach characteristics on Taylors Arm

Area	Valley Distance (km)	Valley Slope	Stream Distance (km)	Stream Slope	Sinuosity
T1-Tidal Limit	50.50	0.0028	72.75	0.0020	1.44
T1-T3 (stable)	13.25	0.0057	18.50	0.0041	1.40
T3-T6 (unstable)	11.00	0.0015	15.00	0.0011	1.36
T7-T11 (Stable)	21.75	0.0019	33.00	0.0013	1.52

Table 4.3: Reach characteristics on North Arm

Area	Valley Distance (km)	Valley Slope	Stream Distance (km)	Stream Slope	Sinuosity
N1-Tidal Limit	41.00 km	0.0028	55.00 km	0.0021	1.34
N2-N5 (Eroded)	27.38 km	0.0025	37.25 km	0.0018	1.36
N1-N2	4.54 km	0.0058	5.5 km	0.0047	1.22
N6-N7	6.38 km	0.0025	9.50 km	0.0017	1.49

Table 4.4: Reach characteristics on Missabotti Creek

Area	Valley Distance (km)	Valley Slope	Stream Distance (km)	Stream Slope	Sinuosity
M1-Nth Arm Jn	14.13 km	0.0040	18.50 km	0.0031	1.31
M1-M3	8.88 km	0.0051	11.75 km	0.0039	1.32
M3-North Arm Jn	5.25 km	0.0021	6.75 km	0.0016	1.29
Nth Arm Jn - Tidal Limit	7.00 km	0.0026	11.25 km	0.0017	1.61

Table 4.5: Reach characteristics on South Arm

Area	Valley Distance (km)	Valley Slope	Stream Distance (km)	Stream Slope	Sinuosity
S1-Tidal Limit	19.0 km	0.0039	26.25 km	0.0029	1.38
S1-S3	5.50 km	0.0064	6.75 km	0.0052	1.23
S3-S5	10.50 km	0.0029	15.25 km	0.0020	1.45

Buckra Bendinni Jn - Tidal Limit	5.13 km	0.0025	6.75 km	0.0019	1.32

Table 4.6: Reach characteristics on Buckra Bendinni Creek

Area	Valley Distance (km)	Valley Slope	Stream Distance (km)	Stream Slope	Sinuosity
B1-Sth Arm Jn	19.38 km	0.0026	23.50 km	0.0021	1.21
B1-B2	8.00 km	0.0030	9.25 km	0.0026	1.16
B2- Junction	11.38 km	0.0023	14.25 km	0.0018	1.25
Jn -Tidal Limit	5.13 km	0.0025	6.75 km	0.0019	1.32

Table 4.7: Reach characteristics on Deep Creek

Area	Valley Distance (km)	Valley Slope	Stream Distance (km)	Stream Slope	Sinuosity
D1-Tidal	9.75 km	0.0038	12.25 km	0.0030	1.26
D1-D2	3.75 km	0.0048	5.00 km	0.0036	1.33
D2-D3	4.75 km	0.0032	6.00 km	0.0025	1.26

Table 4.8: Reach characteristics on Warrell Creek

Area	Valley Distance (km)	Valley Slope	Stream Distance (km)	Stream Slope	Sinuosity
W1-Tidal Limit	16.00 km	0.0021	22.25 km	0.0015	1.39
W1-W2	4.50 km	0.0020	5.38 km	0.0017	1.19
W2-W3	9.00 km	0.0021	13.88 km	0.0014	1.54

The hydraulic features calculated for each site are presented in Table 4.9. Plots for catchment area versus Manning equation-derived bankfull discharge (Figure 4.2), versus HEC-RAS derived bankfull discharge (Figure 4.3) and versus bankfull width (Figure 4.4) show sites where the channel is relatively larger or smaller than other streams in the catchment. Generally speaking, most sites retain their position above or below the line of best fit regardless of which one of the three parameters is used. The sites that are above the line of best fit generally correspond to sites that are very unstable and are experiencing bed and bank erosion problems.

Table 4.9: Hydraulic data calculated for each site in the Nambucca catchment

(Methods used for collecting the data in this table are outlined in section 4.3)

Site	Catchment Area (ha)	Gradient	Manning's Q_b (m^3/s)	HEC-RAS Q_b (m^3/s)	HEC-RAS Q_m (m^3/s)	HEC-RAS Q_m/Q_b (%)	Bankfull Recurrence Interval	Height to high f'plain (m)	Valley Width (m)	Bankfull Width (m)	Max.stable B'full width $4.54Q^{0.33}$	% overwide	Gross Stream Power (ω)	Specific Str. Power (ω/m^2)	Manning's n
T1	3168	0.0067	129.4	26.4	50.9	193	0.5yr	3.5	95	23	23	-	8501	370	0.050
T2	5415	0.0025	129.2	46.5	46.5	100	2 yr	4.0	140	35	23	52	3182	91	0.040
T3	11919	0.0018	306.2	246.6	111.2	45	10 yr	4.2	170	37	29	28	5417	146	0.040
T4	15845	0.0012	528.8	291.4	155.1	53	10 yr	5.2	250	42	36	17	3412	81	0.040
T5	18405	0.0013	990.2	584.9	201.9	35	100yr	8.5	210	57	44	30	12620	221	0.040
T6	19550	0.0013	260.3	138.2	177.7	129	0.5 yr	4.0	160	37	28	32	3325	90	0.040
T7	20120	0.0014	288.3	60.1	183.8	306	0.3 yr	4.2	135	40	29	38	3981	100	0.050
T8	21480	0.0019	509.9	187.2	187.2	100	2 yr	8.4	160	35	35	-	9500	271	0.040
T9	32304	0.0011	517.6	243.1	243.1	100	1 yr	7.5	120	55	36	53	5597	102	0.055
T10	33846	0.0012	752.2	451.1	322.9	72	2 yr	7.2	210	42	40	5	8861	211	0.040
T11	37444	0.0011	596.1	343.1	343.1	100	1 yr	8.6	150	45	37	22	6412	142	0.050
N1	4001	0.0044	175.9	48.1	48.1	100	1 yr	2.8	95	30	30	-	7579	253	0.050
N2	6937	0.0057	452.0	211.3	144.4	68	2 yr	3.3	150	40	34	18	26754	669	0.040
N3	11562	0.0018	649.0	424.0	144.3	34	10 yr	5.6	250	65	39	67	11456	176	0.035
N4	13367	0.0020	1300.9	509.8	185.0	36	20 yr	5.0	270	85	50	70	24020	283	0.030
N5	15064	0.0020	1674.2	657.9	261.6	40	100yr	8.0	290	70	54	30	32782	468	0.025
N6	24067	0.0018	866.4	497.9	330.7	66	2 yr	6.6	270	70	43	63	15311	219	0.035
N7	42998	0.0011	584.0	379.2	353.3	93	1 yr	9.0	380	48	38	26	6044	126	0.045
M1	214	0.0133	125.2	23.8	12.1	51	5 yr	4.0	115	32	23	39	16291	509	0.033
M2	4024	0.0021	263.0	94.8	69.0	73	2 yr	3.5	180	45	29	55	5421	120	0.045
M3	6182	0.0021	295.6	172.2	134.4	78	2 yr	6.0	340	25	30	-	5064	203	0.040
M4	7048	0.0016	231.4	135.9	76.9	56	5 yr	5.5	280	50	28	79	3626	73	0.050
S1	874	0.0100	52.2	19.0	15.0	79	2 yr	2.0	70	15	17	-	5100	340	0.050
S2	2435	0.0050	321.7	125.6	50.2	40	5 yr	3.1	140	40	31	29	15763	394	0.050
S3	4605	0.0031	291.4	169.4	91.5	54	2 yr	3.7	110	30	30	-	8844	295	0.035
S4	6460	0.0027	176.0	50.0	51.7	103	0.5yr	3.5	120	20	25	-	4660	233	0.060
S5	17162	0.0012	488.5	189.0	187.9	101	2 yr	6.2	180	45	36	25	5758	128	0.050
B1	3175	0.0047	392.8	146.2	56.6	39	10 yr	2.4	180	22	33	-	18095	823	0.030
B2	5880	0.0028	557.7	233.5	85.6	37	50 yr	3.5	170	60	37	62	15019	250	0.033
B3	7250	0.0009	141.2	114.8	59.6	52	2 yr	4.8	170	35	24	45	1321	38	0.060
D1	463	0.0038	12.0	12.0	12.0	100	1 yr	3.5	50	9	10	-	442	49	0.055
D2	1729	0.0032	73.5	31.8	31.8	100	1 yr	4.5	80	14	19	-	2304	165	0.055
D3	5372	0.0023	225.1	99.0	59.7	60	2 yr	4.1	120	40	28	43	5069	127	0.060
W1	3914	0.0018	28.8	20.4	27.6	135	0.5yr	3.5	70	11	14	-	507	46	0.075
W2	7268	0.0014	71.9	31.1	33.9	109	0.6yr	4.3	110	20	19	5	980	49	0.090
W3	19000	0.0013	160.0	107.6	73.9	69	2 yr	5.5	230	50	28	79	2023	40	0.070

Notes: Q_b = Bankfull Discharge
Q_m = Mean Annual Flood Discharge
Stream Power (ω) derived from using Manning's Q_b
Bankfull Recurrence Interval derived from cross-sections used for the HEC-RAS formula

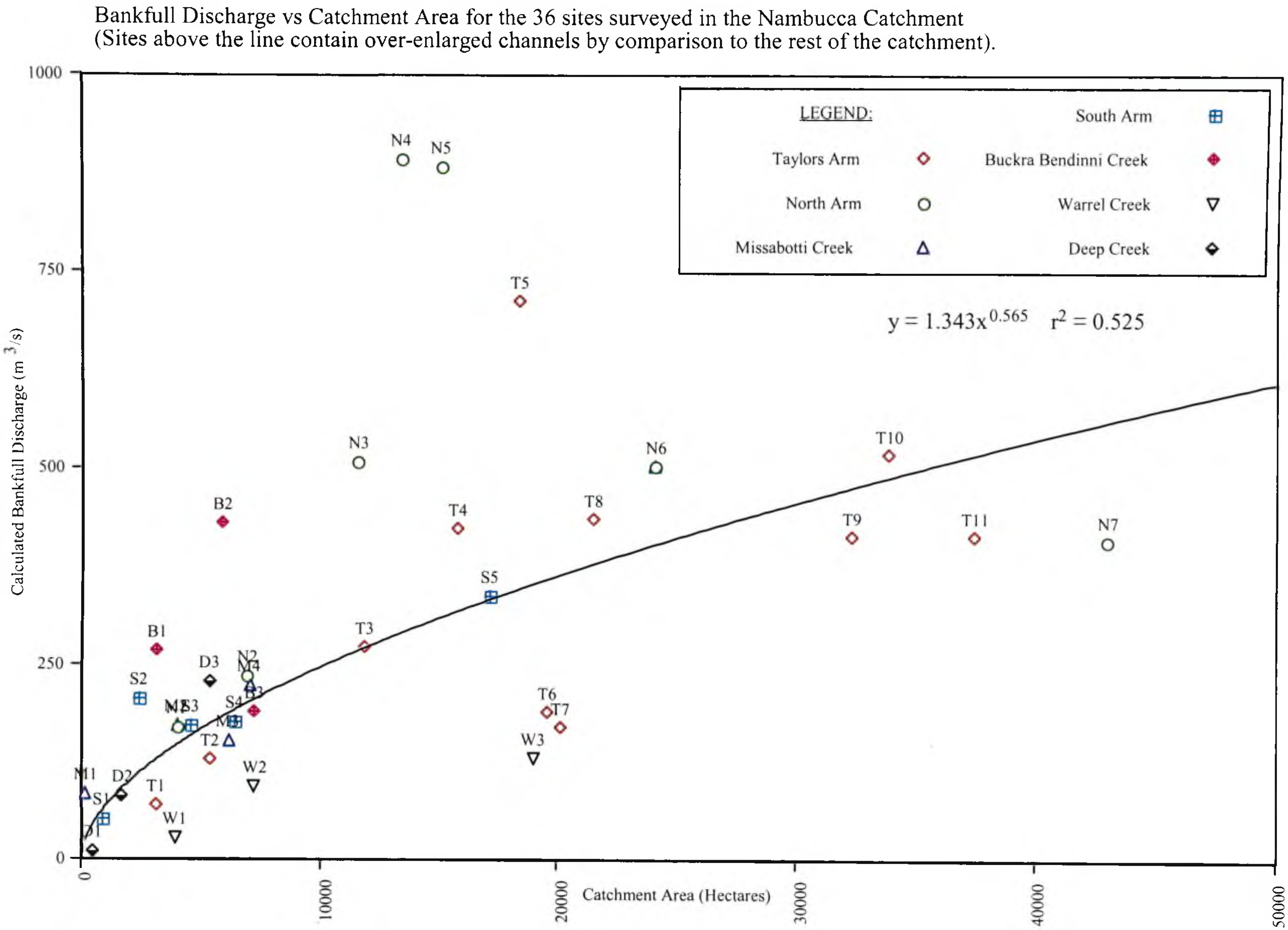


Figure 4.2: Bankfull discharge versus catchment area for study sites in the Nambucca catchment

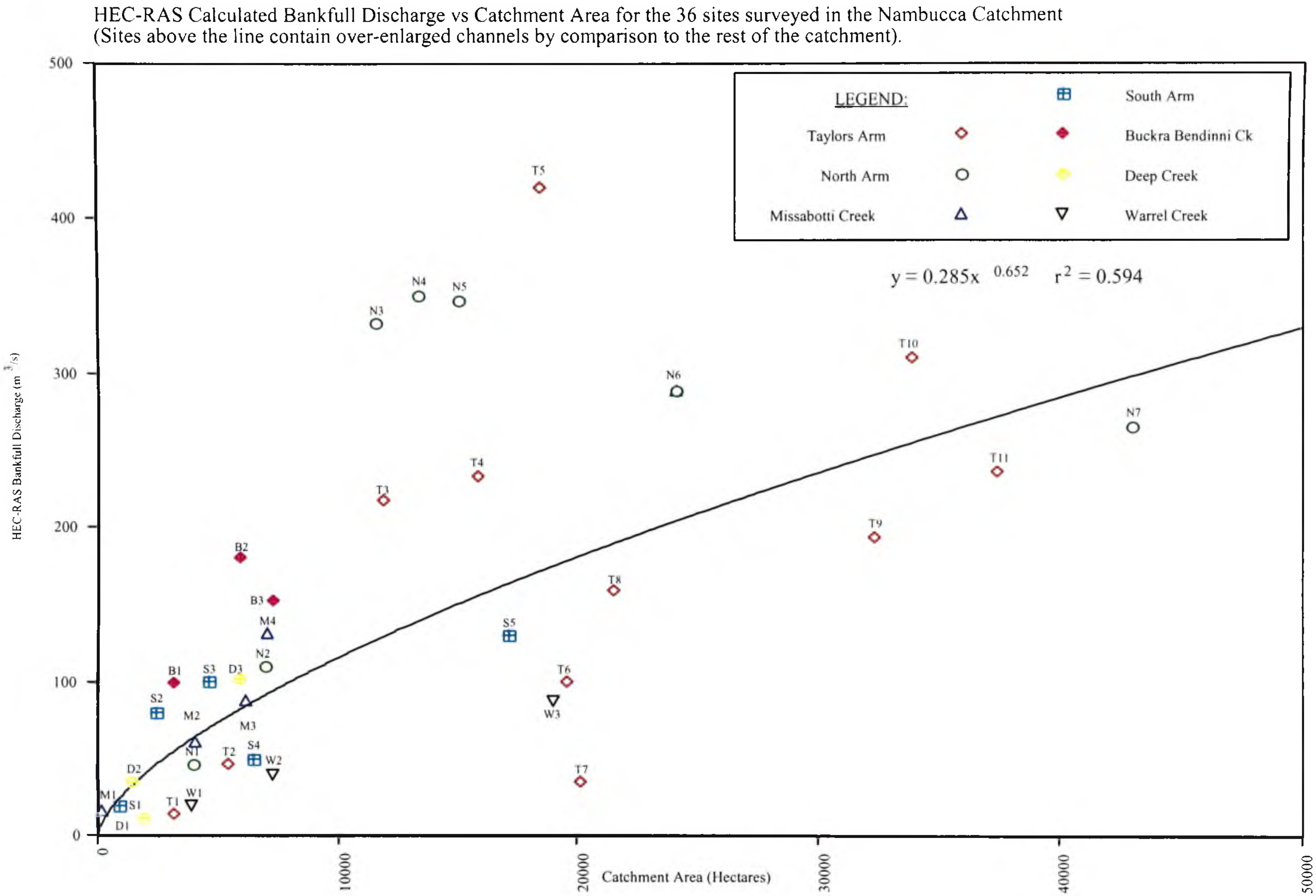


Figure 4.3: HEC-RAS calculated bankfull discharge vs catchment area for study sites in the Nambucca catchment

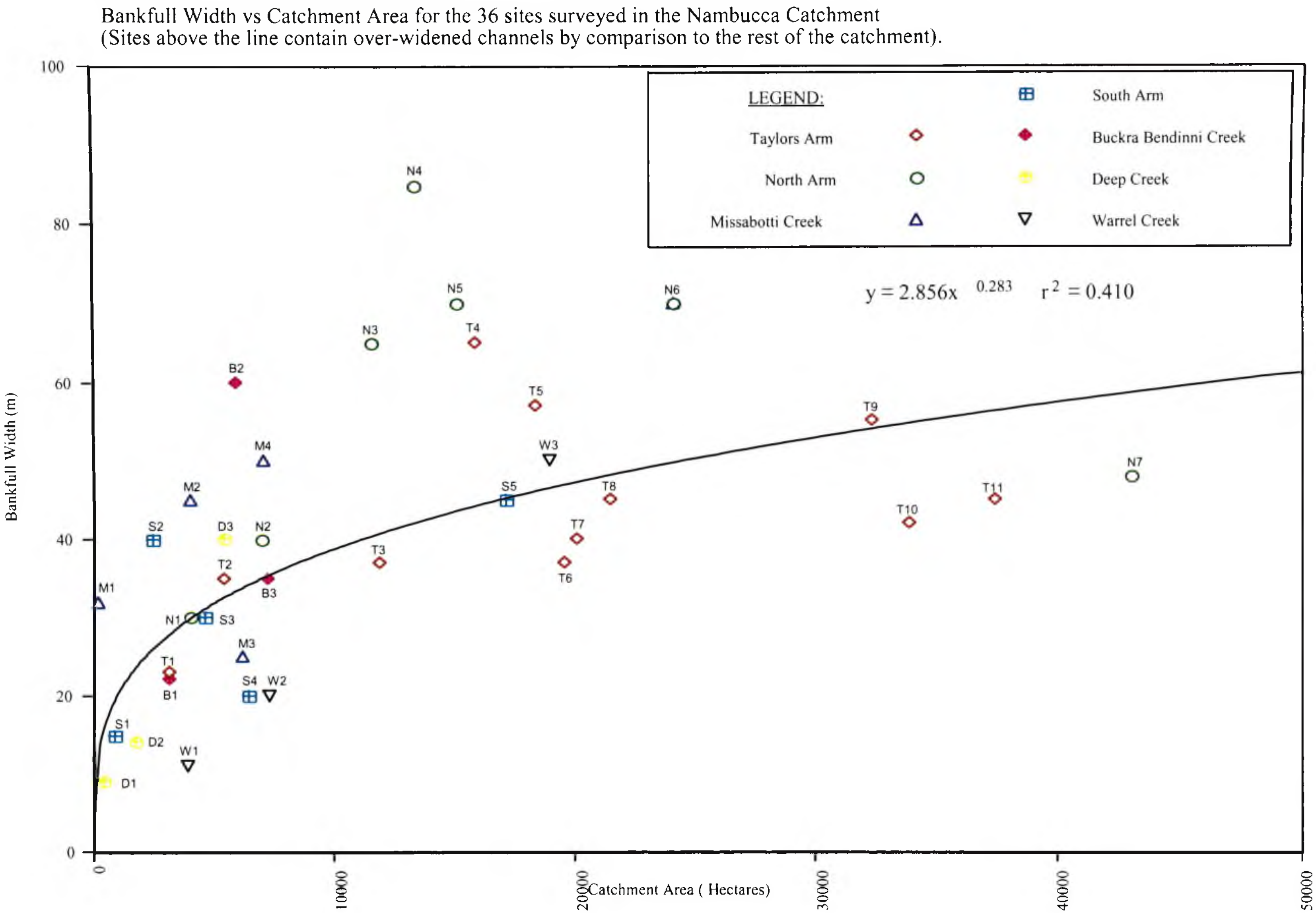


Figure 4.4: Bankfull width versus catchment area for study sites in the Nambucca catchment

4.4 Sediment Analysis

4.4.1 Introduction

A thorough analysis of streambed sediment size and lithology provides data that can assist stream managers interpret the patterns and behaviour of stream erosion and bedload transport. The results of such analyses help derive transport rates and determine the presence or absence of bed armouring.

The analysis of streambed sediment within the Nambucca catchment provides data for 36 sites across the 7 tributaries of the Nambucca catchment. This detailed study is the first of its kind in a NSW north coast river catchment. Data has been collected in the non-tidal section for the major trunk and tributary streams.

In this study, alluvial sediment has been sampled by two methods. Firstly, the Wolman method (Wolman, 1954) was used to measure the size and lithology of the clasts on the surface of the riffles. Secondly, the surface layer was removed and a bulk sample collected, which was then sieved in the field and laboratory. The mean size is used as a representative index of grain size of the surface and subsurface sample at each site, and the full grain size distribution was recorded for the subsurface sample.

4.4.2 Wolman Survey

4.4.2.1 Aim

The Wolman method (Wolman, 1954) is used to obtain an estimate of the size and lithology of the surface armours on accessible riffles or point bars. The method records the size of three perpendicular axes of the grains (a- ,b- and c-axis). The intermediate, or b-axis, is important for use in hydraulic equations as an indication of the size and hydraulic properties of the clast, the other two axes sometimes being used to provide indices of particle shape. As the Wolman method measures only clasts lying at the surface, it provides a useful index of the degree of sorting by providing the size of clasts in the bed material armour for comparison with the size of the clasts obtained from bulk samples beneath the surface.

4.4.2.2 Method

In this study, a 30-metre tape measure was oriented as a downstream transect over selected riffles. At every 0.5 m interval the stone directly beneath the tape was selected and the a, b and c-axes were recorded. The lithology of the stone was noted as quartz, phyllite, schistose sandstone or other (very rare). If two adjacent sampling points happened to lie over the same very large stone the second observation was ignored and an additional point added to the end of the transect. If the point lay over a sand patch, the size was recorded as 'sand' (and given the dimensions of 1mm x 1mm x 1mm). This method gave a sample of up to 61 stones for each site from which the grain size data for the site was determined.

It is noted that this method has been criticised by a number of authors (e.g. Kellerhauls and Bray, 1971) who question the accuracy of particle-size distributions obtained from pebble count. Fractions finer than 1 mm are not considered and this can then affect calculations of different diameter percentiles. Estimates of bedload transport rates, for example, vary significantly if the bed-material percentile particle-size used for the computation varies slightly (Gessler *et al.* 1993).

Despite criticism of the method, it has been assessed to be the most suitable for the Nambucca catchment given the uniformity of the quartz reaches in the eroded middle and lower reaches. The method also assisted in understanding the lithology of the surface material and the D_{50} was a useful co-efficient for the homogenous bed surface in many reaches.

4.4.2.3 Results

The statistical results from the Wolman Survey can be seen in Table 4.10.

Table 4.10: Statistical results from the Wolman Survey of the Nambucca catchment tributaries

Site	Mean and Standard Deviation (mm)	Range (mm)	% Quartz
T1	149 ± 79	70 - 228	21
T2	111 ± 63	50 - 126	19
T3	40 ± 23	17 - 63	51
T4	30 ± 16	14 - 46	51
T5	17 ± 14	3 - 31	77
T6	39 ± 16	23 - 55	61
T7	14 ± 7	7 - 21	78
T8	39 ± 16	23 - 55	81
T9	16 ± 9	7 - 25	86
T10	20 ± 11	9 - 31	86
T11	25 ± 21	4 - 46	88
N1	84 ± 44	40 - 128	13
N2	54 ± 35	19 - 89	52
N3	32 ± 22	10 - 54	76
N4	28 ± 18	10 - 46	92
N5	26 ± 17	9 - 43	93
N6	22 ± 11	11 - 33	95
N7	19 ± 10	9 - 29	98
M1	81 ± 32	49 - 113	50
M2	36 ± 21	15 - 57	67
M3	37 ± 26	11 - 63	73
M4	22 ± 14	8 - 36	92
S1	117 ± 90	27 - 207	2
S2	77 ± 32	45 - 109	4
S3	85 ± 41	44 - 126	7
S4	37 ± 15	22 - 52	35
S5	17 ± 8	9 - 25	98
B1	121 ± 54	67 - 175	11
B2	41 ± 19	22 - 60	44
B3	28 ± 11	17 - 39	71
D1	16 ± 10	6 - 26	85
D2	14 ± 5	9 - 19	97
D3	25 ± 11	14 - 36	92
W1	11 ± 8	3 - 19	72
W2	10 ± 6	4 - 16	88
W3	14 ± 10	4 - 24	95

4.4.3 Sediment Sieving

4.4.3.1 Aim

Sieving bulk samples of the bed sediments provides a representation of the full range of stream bed-sediment size at a site, not just the size of the surface deposit as determined from a Wolman survey. By obtaining both, entrainment functions can be used to determine what percentage of the bed material can be transported once the surface armour is eroded and the bed disrupted.

4.4.3.2 Method

After the Wolman Survey was completed, the surface layer of sediment was scraped off an area of about 1m^2 on an exposed riffle. A symmetrical pit (i.e. equal diameter and depth) was dug and all of the sediment from the pit was passed through a sequence of sieves of decreasing mesh size (90, 63, 45, 31.5, 22.4, 16 and 11.2mm). These sizes correspond to 0.5 phi size intervals [phi = -3.33 log (mm)] used in the phi scale (Appendix 3). The largest stone caught in the largest sieve was retained and weighed individually in order to determine the maximum clast size within the distribution. A sample of the sediment passing through the smallest field sieve (11.2mm) was collected and taken back to the laboratory where it was dried, weighed and passed through a series of 9 sieves, at half phi intervals, ranging from 5.63mm (-2.5 phi) to 0.5 mm (+1.0 phi). The laboratory results were then proportionated to the total weight of the field sample to determine a complete size distribution from both the field and laboratory results (Appendix 5).

In order to ensure that the sample was large enough to accurately accommodate the largest stone as less than 5% of the total volume sieved it was necessary to sieve over 100kg of material at each site. This ensured compatability for all sites and at no site did the largest stone sieved account for greater than 3% of the total volume of material.

4.4.3.3 Results

The results of the bedload sieving for all 36 sites are represented in Table 4.11.

Table 4.11: Results of bedload sieving analysis for the Nambucca catchment

[Results indicate the grain size (mm) for each relevant percentile]

Site	5% is larger than(mm)	16% is larger than (mm)	50% is larger than (mm)	84% is larger than (mm)	95% is larger than (mm)
T1	96.58	91.52	32.90	2.82	2.29
T2	95.70	88.67	21.58	1.67	0.70
T3	64.37	41.96	15.01	2.28	2.35
T4	37.87	25.75	10.70	2.26	1.06
T5	19.14	18.27	6.02	1.65	0.81
T6	50.94	34.20	10.49	1.58	0.64
T7	24.54	18.05	6.26	1.68	0.62
T8	41.83	27.52	8.44	2.40	0.92
T9	31.09	25.25	11.30	3.02	1.48
T10	30.98	15.12	6.55	2.41	1.21
T11	31.84	22.13	11.19	2.92	1.74
N1	95.48	86.41	25.71	3.41	1.17
N2	69.56	51.00	17.22	2.14	0.86
N3	61.90	36.28	13.46	2.32	0.98
N4	49.40	31.79	9.85	2.51	0.91
N5	45.52	21.95	6.20	1.51	0.65
N6	31.32	20.61	8.31	1.95	0.58
N7	28.31	17.19	8.18	2.42	0.97
M1	87.75	55.09	19.42	4.78	1.94
M2	67.09	28.42	10.86	2.92	1.09
M3	44.22	27.96	9.55	3.71	1.15
M4	41.03	31.37	18.37	6.57	3.01
S1	95.17	82.14	26.37	4.25	1.74
S2	91.06	75.25	41.06	21.32	10.15
S3	89.72	60.09	19.41	1.67	0.60
S4	43.67	33.94	13.46	2.59	0.77
S5	35.32	22.07	9.35	2.56	0.95
B1	97.06	93.05	42.55	6.24	2.60
B2	62.09	43.09	17.67	5.99	2.87
B3	52.63	33.27	11.54	2.65	0.87
D1	34.46	20.65	6.86	1.78	0.77
D2	22.06	14.98	6.36	1.78	0.92
D3	52.59	35.07	15.23	6.77	4.24
W1	11.39	9.75	4.99	1.90	0.46
W2	11.52	9.19	5.07	1.34	0.58
W3	11.56	10.29	6.26	1.35	0.72

4.4.4 Interpretation of Coarse Sediment Distribution

The sediment analyses have revealed a number of fairly consistent relationships between sediment size and lithology and other catchment variables. For instance, all catchments except Deep Creek and Warrell Creek show a marked decline in sediment size downstream. The gravel present is very poorly sorted at nearly all sites (note standard deviations in Table 4.10). In addition, in all catchments there is a marked and consistent increase in the proportion of quartz clasts downstream.

A summary of the statistical relationship between variables can be seen in Table 4.12. The values given are r^2 values that are a representative figure indicating the statistical relationship between the two variables graphed for each stream. The r^2 values significant at the 5% level are shown in bold. 'Linear' refers to a best-fit straight line through the data set, whilst 'curve' refers to a polynomial best fit. A significant relationship can be inferred if the r^2 value is greater than the critical r^2 value.

Table 4.12: Summary of statistical relationships between variables for each stream

Relationship	Type of Fit	Taylors Arm	North Arm	Missabott Creek	South Arm	Buckra Bendinni Creek	Deep Creek	Warrell Creek	Total Catchment
Critical r^2 value needed (at 5% Significance)	->	*0.602*	*0.754*	*0.878*	*0.811*	*0.950*	*0.990*	*0.990*	*0.330*
Distance vs Armour Size	Linear->	0.560	**0.827**	**0.932**	**0.916**	0.826	0.815	0.756	**0.469**
	Curve->	**0.934**	**0.932**	**0.993**	**0.939**	0.930	N/A	N/A	**0.705**
Distance vs Sub-Surf Size	Linear->	0.509	**0.834**	0.323	0.629	0.857	0.726	0.726	**0.388**
	Curve->	**0.947**	**0.927**	0.358	0.634	**0.950**	N/A	N/A	**0.530**
Armour Size vs %Quartz	Linear->	**0.727**	**0.989**	0.828	0.758	0.833	0.008	N/A	**0.398**
	Curve->	**0.759**	**0.990**	**0.969**	**0.961**	**0.980**	N/A	N/A	**0.413**
Sub-Surf. Size vs %Quartz	Linear->	**0.772**	**0.970**	0.137	0.520	0.854	0.620	N/A	0.328
	Curve->	**0.818**	**0.978**	0.167	0.609	**0.988**	N/A	N/A	0.328
Distance vs %Quartz	Linear->	**0.826**	**0.847**	**0.939**	**0.905**	**0.969**	0.121	N/A	**0.450**
	Curve->	**0.916**	**0.951**	**0.957**	**0.981**	**0.970**	N/A	N/A	**0.477**

The statistical relationships shown in Table 4.12 are displayed graphically for each stream in Figures 4.5 to 4.10. The graphs indicate any relationships between; stream distance, armour size, sub-surface grain size and the percentage of quartz in the surface layer (Wolman survey).

Figure 4.5a: Distance vs Armour Grain Size on Taylors Arm

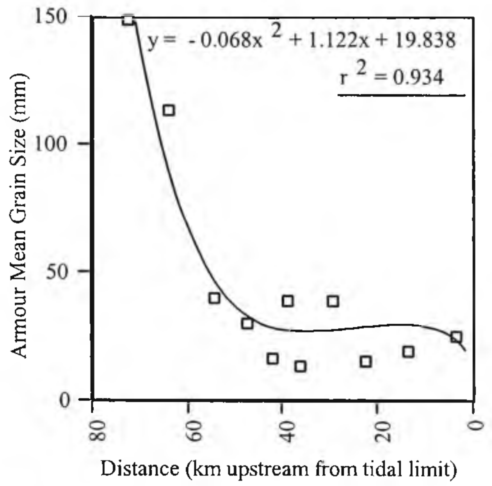


Figure 4.5b: Distance vs Sub-surface Grain Size on Taylors Arm.

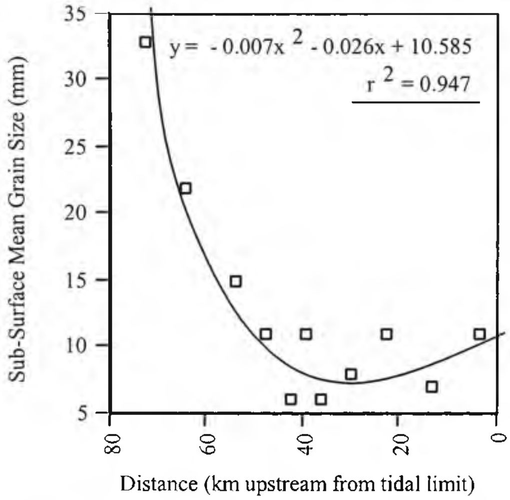


Figure 4.5c: Sub-surface Grain Size vs %Quartz on Taylors Arm

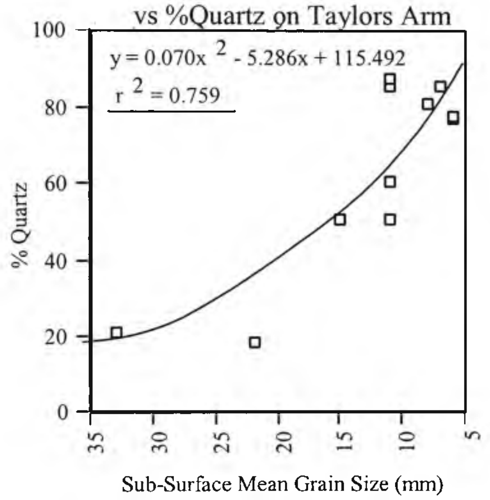


Figure 4.5d: Armour Grain Size vs %Quartz on Taylors Arm

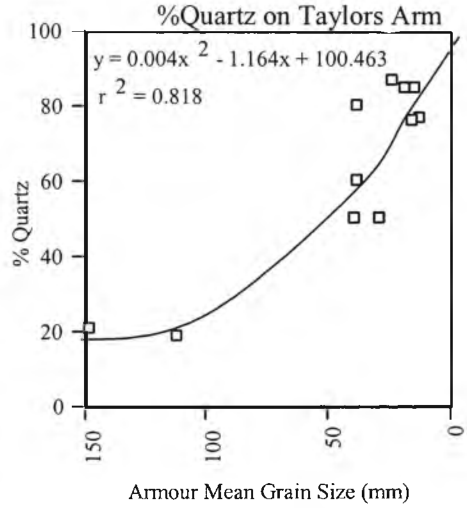


Figure 4.5e: Distance vs %Quartz on Taylors Arm

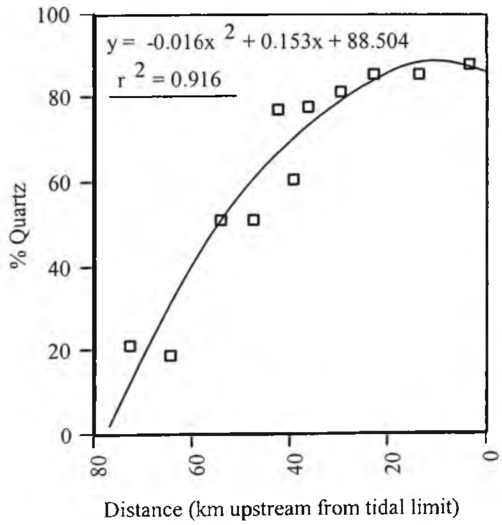


Figure 4.5f: Armour Grain Size vs Sub-Surface Grain Size on Taylors Arm

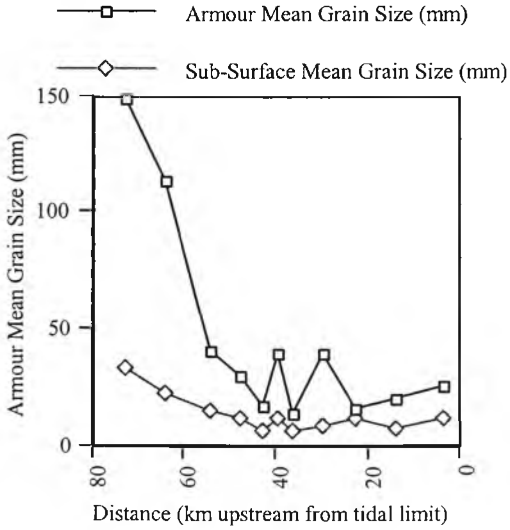


Figure 4.5: Sediment curves for Taylors Arm
(statistically significant r^2 value underlined)

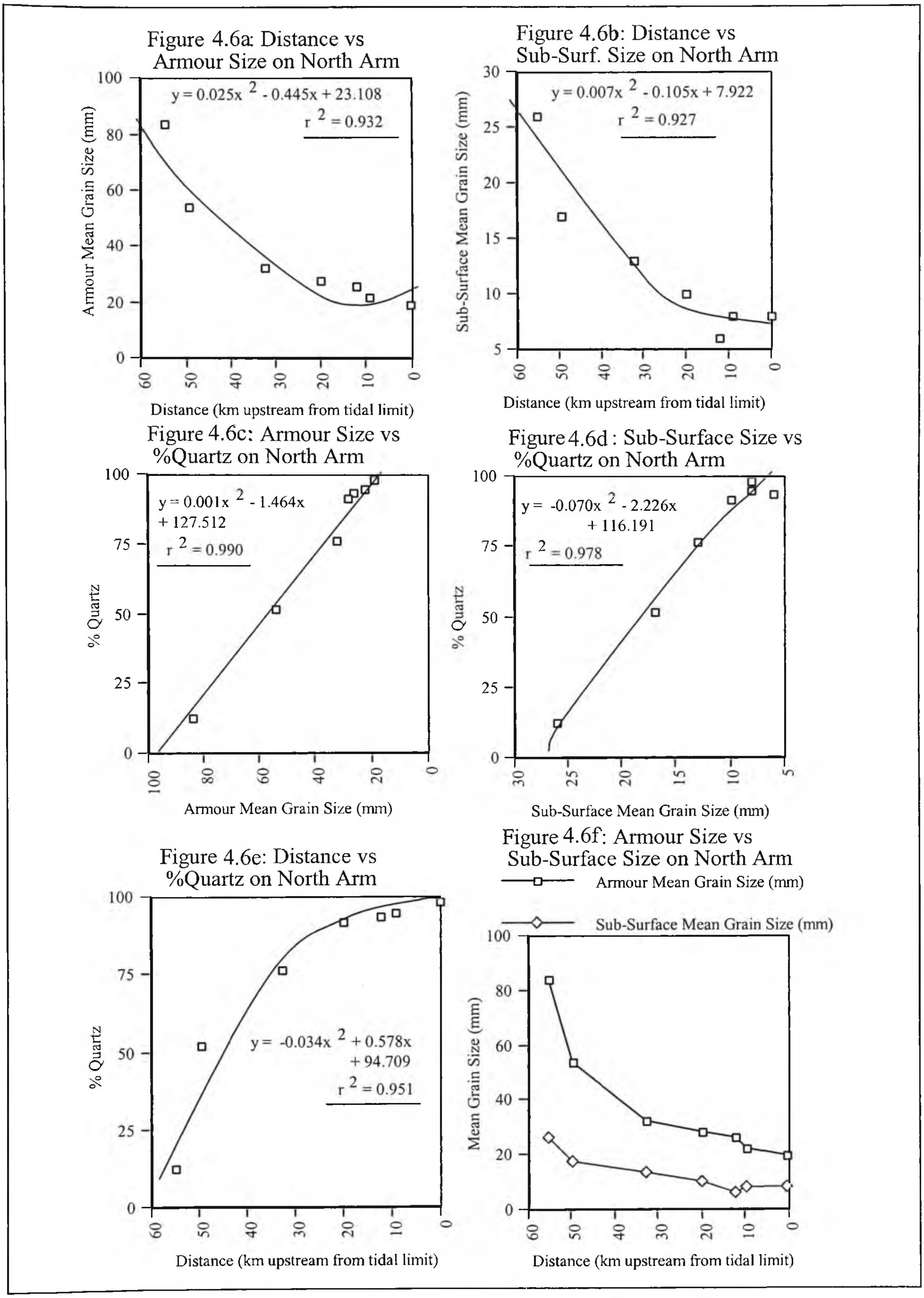


Figure 4.6: Sediment curves for North Arm
(statistically significant r^2 value underlined)

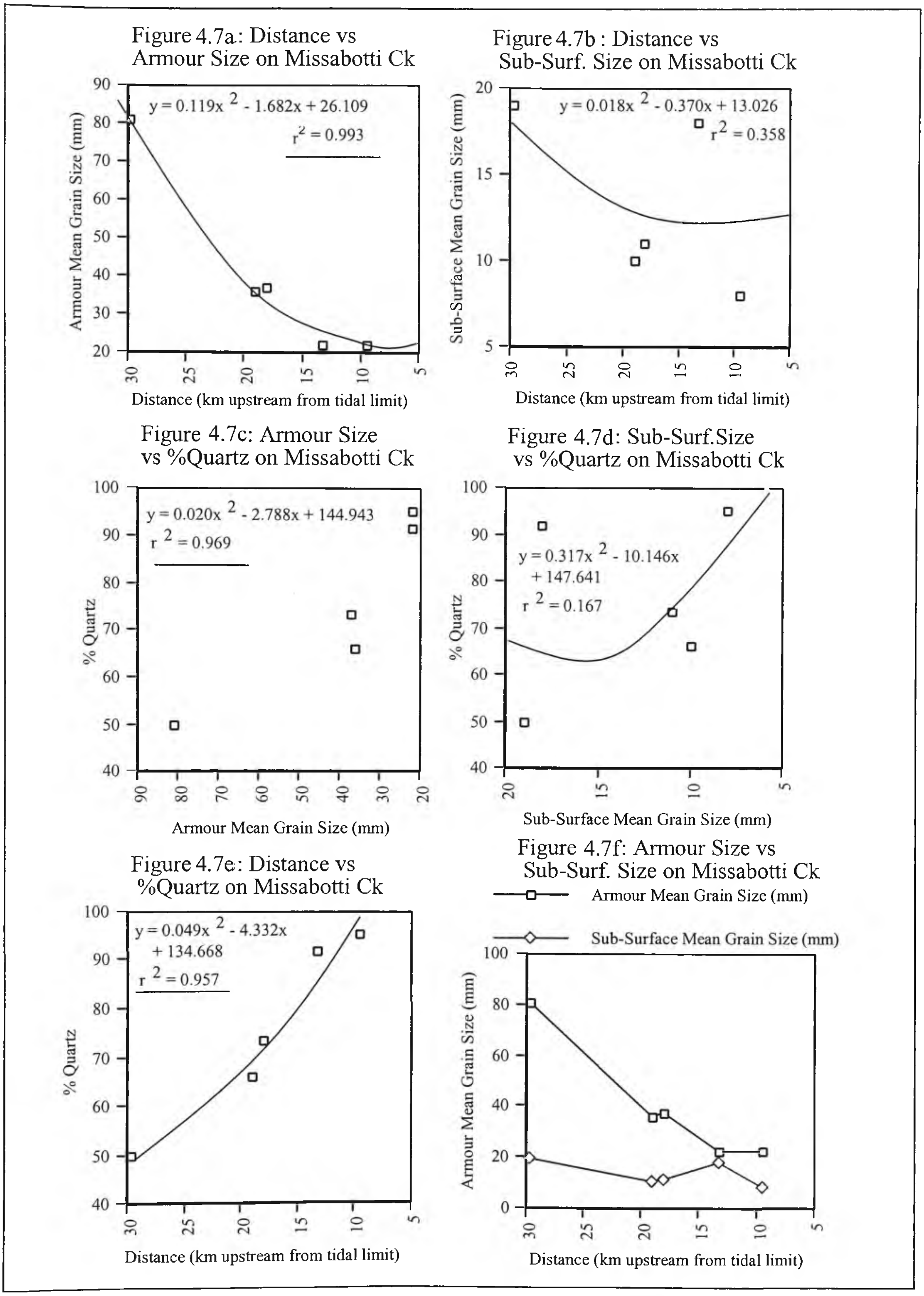


Figure 4.7: Sediment curves for Missabotti Creek
(statistically significant r^2 value underlined)

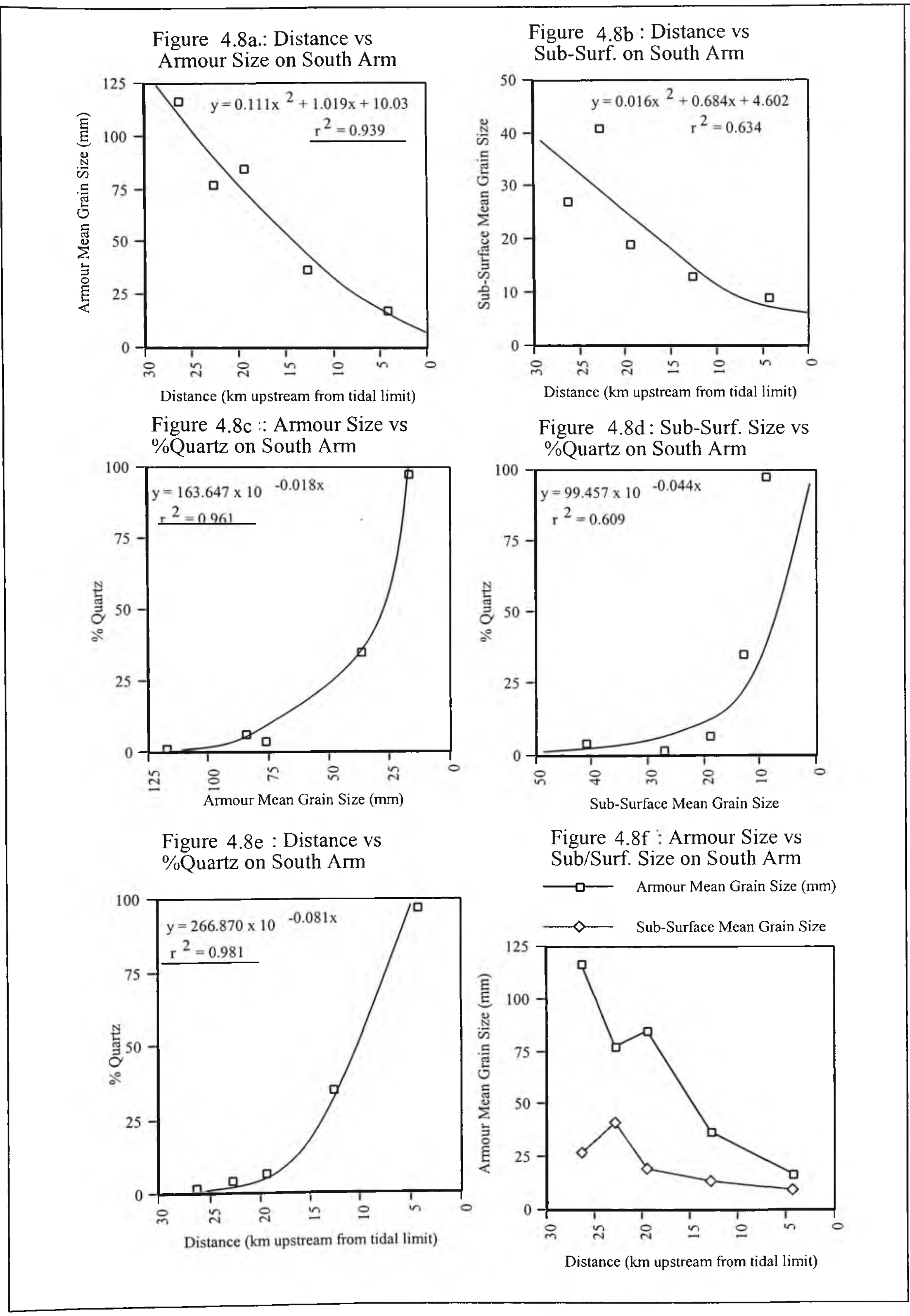


Figure 4.8: Sediment curves for South Arm
(statistically significant r^2 value underlined)

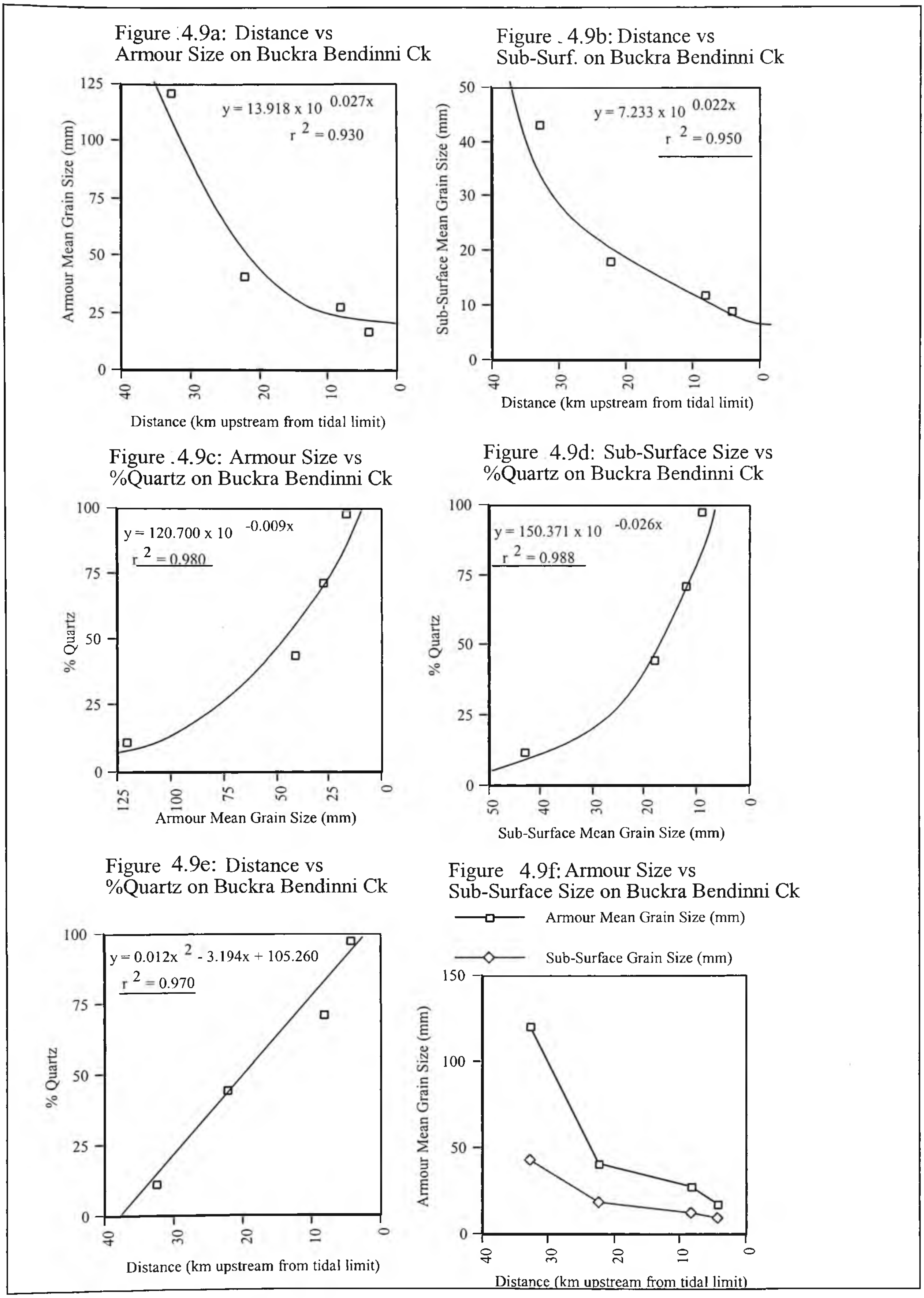


Figure 4.9: Sediment curves for Buckra Bendinni Creek
(statistically significant r^2 value underlined)

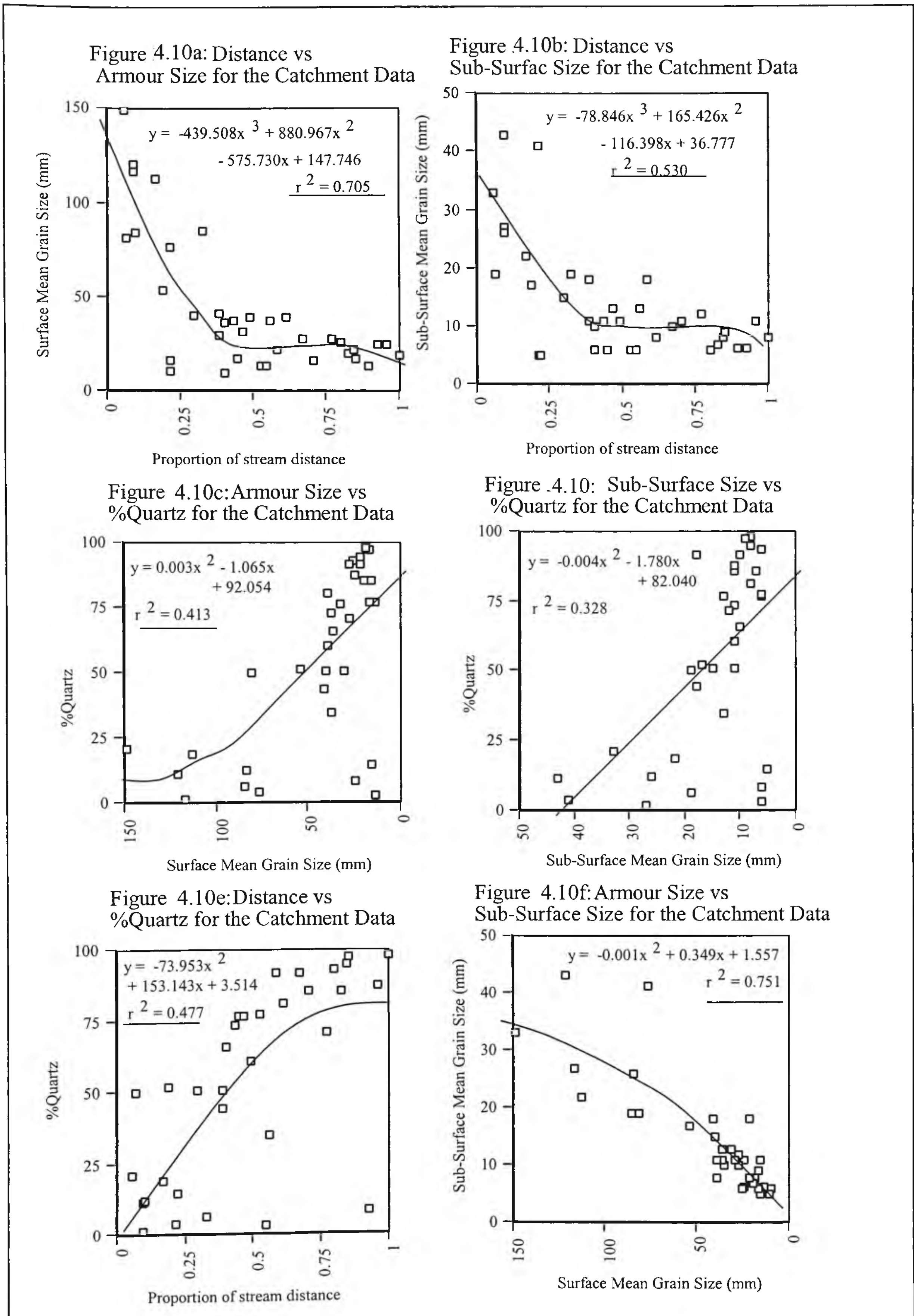


Figure 4.10: Sediment curves for the 36 sites sampled in the Nambucca catchment
(statistically significant r^2 value underlined)

4.4.5 *Discussion*

From detailed analyses of the sediment characteristics on all seven streams, some general trends and interesting exceptions have emerged. The following discussion considers only Taylors Arm, North Arm, Missabotti Creek, South Arm and Buckra Bendinni Creek in detail. Deep Creek and Warrell Creek each had too few sampling sites to show any clear downstream pattern.

4.4.5.1 Grain Size Change Downstream

All five streams show a rapid downstream decline in grain size that slows near the tidal limit. Taylors Arm shows a sharp decline in the headwaters and little change in the middle to lower catchment. In general the surface armour is roughly equivalent to the fifth to sixteenth percentile values for the sub-surface sediment. With the possible exception of Buckra Bendinni Creek, there is a poor or non-existent relationship between the ratio of bed armour to sub-surface size and distance downstream. However, on the larger streams it is clear that the upstream 2-3 sites have a considerably higher ratio than the remaining sites.

4.4.5.2 Grain Size Change with Gradient

The use of map gradients (derived from 10 m contour intervals) to infer stream gradients at each site did not show a relationship with grain size as clearly as distance downstream, but a trend is still present. Stream long profiles can be seen in Appendix 6. Steeper sites definitely have coarser sediment, but the relationship is poor for the less-steep sites. Due to the difficulty in accurately determining stream gradients from map slopes, elevation of the valley floor was used as a surrogate. The results were almost identical for the relationship with distance and hence are not shown here.

4.4.5.3 Quartz Composition of the Bed Material

Along all five streams there is a strong downstream increase in the proportion of quartz. In both Taylors Arm and North Arm the trend is very marked in the downstream reaches. There is also a strong negative relationship between the percentage of quartz and the mean grain size in all creeks, except Missabotti Creek.

4.4.5.4 Reasons for Grain-Size and Mineralogical Changes Downstream

Downstream fining in a gravel-bed river is customarily attributed to a combination of abrasion (of moving particles and of those over which they move) and sorting (size selection during entrainment, transport and deposition) (Ferguson et al., 1996) but isolating the relative importance of each of these processes in the field is problematic (Werritty, 1992). There are many studies examining downstream fining (eg. Hoey and Ferguson, 1994; Seal and Paola, 1995; Pizzuto, 1995; Ferguson et al., 1996) all identifying the importance of abrasion and selective transport.

Examination of the data in Table 4.10 indicates that the surface bedload throughout the Nambucca catchment is poorly sorted. Standard deviations are large for almost every site in the catchment. Paola et al. (1992) attribute downstream fining in poorly sorted gravel to selective transport, and Andrews and Parker (1987) have demonstrated that poorly sorted gravels readily develop an armour layer. Selective transport could remove the smaller and mostly cubic-shaped quartz leaving the large and mostly elongate phyllite behind. Comparison of the armour mean and the subsurface mean at almost all upstream sites show a marked difference, indicating substantial bed armouring which suggests the important role of selective transport.

However, it is also apparent that abrasion can readily reduce the size of the brittle and relatively soft phyllite, whilst the same process has much more difficulty further fracturing the small quartz clasts found in this catchment. This demonstrates the difficulty in differentiating between abrasion and selective transport in the catchment.

The analysis of bed material on the streams of the Nambucca catchment has established a baseline data set for further reference and comparison. In this catchment a clear inverse relationship exists between the percentage of quartz present and the mean grain size of the armour in most streams. The data presented in this chapter will be related to information from subsequent chapters where stream morphology and changes over time are examined. It is these changes which could shed light on the age of the sub-surface layer and whether this component of the bed material is part of the modern system.

4.5 Channel and Floodplain Morphology

The seven major tributaries of the Nambucca River all exhibit within and between stream differences in parameters such as: floodplain width; floodplain height from the channel bed; the presence and form of within-channel benches and; the nature of vegetative cover.

4.5.1 Valley Units

In order to describe the character of the Nambucca catchment, adjacent individual sites are aggregated down-valley into *valley units* that are defined initially on the basis of their degree of erosion, but also in terms of similar geomorphological characteristics. This approach treats a reach of tributary, including the terraces, floodplains and channel, as a single unit, for these landform features are clearly interrelated. However, downstream changes in geomorphology are transitional and the boundaries between valley units are arbitrary divisions within what is usually a continuum of change. In Missabotti Creek, North Arm, South Arm, Buckra Bendinni Creek and Taylors Arm, there are three fairly consistent valley units; an upper, middle and lower catchment units. Each of these units has been labelled according to the visible status of bed and bank erosion. Because of their relative stability, different geological structures and, the fact that they do not join the Nambucca River prior to the tidal limit, Deep Creek and Warrell Creek are different in character to the rest of the catchment's streams and are therefore treated somewhat separately. A map showing the distribution of the different erosion categories can be seen in Figure 4.11. The detailed description of each valley unit for each sub-catchment is given in Appendix 7.

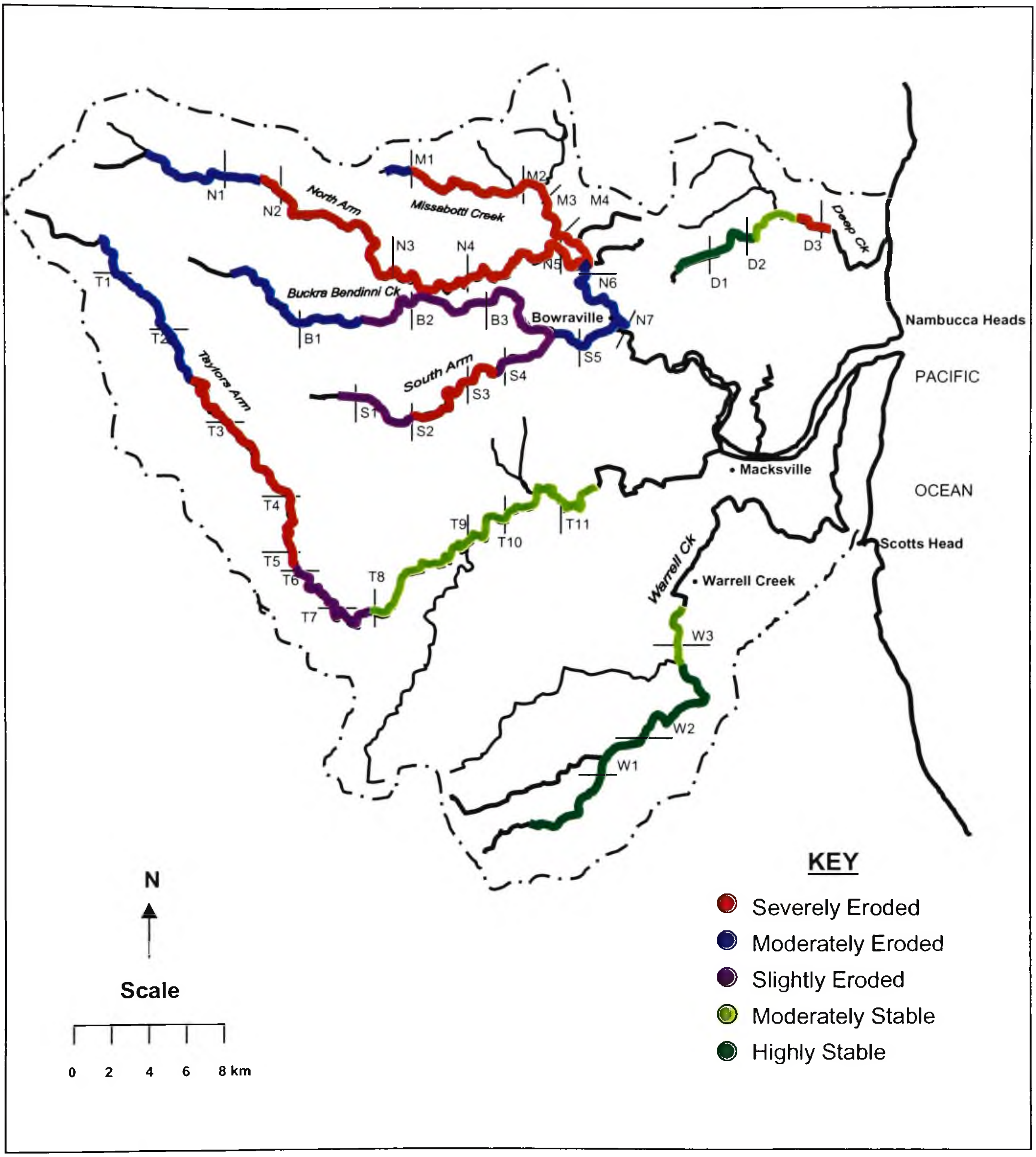


Figure 4.11: Comparative status of channel degradation in the Nambucca catchment

4.5.2 *Terrace and Floodplain Stratigraphy*

The terraces and floodplains of Taylors Arm, North Arm, South Arm, Missabotti Creek, Buckra Bendinni Creek and lower Deep Creek, but excluding Warrell Creek and upper and middle Deep Creek, consist primarily of two distinct units; basal gravels and overlying alluvial silty sands. The alluvium present above the gravel is referred to here as either sandy loam, loam (roughly equal sand and silt components) or clay loam (groups under Northcote system code *Um6.11*). Organic material in the floodplains consists of: (a) localised leaf litter in the grey clay layer within the basal gravels and preserved by previously higher water tables; (b) logs buried at the base of the floodplain and preserved by previously higher water tables, and; (c) charcoal derived from catchment forest fires which is deposited across floodplain loams (and later buried).

4.5.2.1 <u>Basal Gravels</u>

A distinctive feature of the of the upper reaches of Taylors Arm, North Arm, South Arm, Missabotti Creek and Buckra Bendinni Creek is that the basal gravels are usually at least as thick as the overlying fines. Towards the margins of these confining valleys, the gravels and boulders give way to hillslope colluvium and bedrock. Further downstream, as floodplain width increases and channel slope and gravel size decrease, stratigraphic sequences become more complex due to the more extensive preservation of older alluvial deposits and palaeochannels in the wider valleys. Generally speaking, the thickness of gravel decreases and fine alluvium increases downstream.

At several upstream sites, stratigraphic evidence indicates terraces and narrow inset floodplains along these channels (eg. Taylors Arm Site 2; Missabotti Creek Site 1; South Arm Site 1). Whether these upper valley terraces are the product of infrequent extreme depositional-erosional events, or a series of systematic climate and flow regime changes, is not known. Further downstream, the confining terrace topography and associated stratigraphic architecture gives way to one of a wider floodplain stratigraphy. Although terraces are often present here, they are separated by relatively extensive floodplains (eg. Taylors Arm Site 4; North Arm Site 3)

The sedimentology and stratigraphy of the Nambucca catchment floodplains allows an interpretation of their mode of formation. Within the basal units, the gravels are commonly imbricated (Figure 4.14) and laterally extensive, and as such they present

useful evidence of channel migration and bar deposition from the recent past. In the middle and lower reaches of each valley, the basal unit consists of relatively fine textured gravel exposed at the base of cut banks along the river. This material would be a catalyst for widespread cut bank erosion and channel migration. Gravel in the upper layer of the floodplain, however, provides evidence that these channels did not require migration across their entire valley floor to deposit gravel. The gravels are commonly thickest near the current channel and thin towards the valley sides (eg. Taylors Arm, Sites 3, 4, 6, 7, 8, 9, 10 and 11; North Arm, Sites 2, 3, 4, 5 and 7; Missabotti Creek, Sites 2, 3 and 4; South Arm, Sites 4 and 5; Buckra Bendinni Creek, Sites 1 and 3). It appears that lateral reworking of the channels has distributed gravels across most of the valley floor, but that more recently (in geological time) this lateral activity has slowed and the channels have tended to aggrade near the position that many of them occupy today. In other words, the channels were either more energetic in the past and have declined in energy, or their banks have recently become more resistant to erosion, or both. That this particular stratigraphic architecture is so widespread adds weight to the theory of changing floodplain evolution of the Nambucca catchment in the latter stages of valley alluviation. A further examination of this is given in Chapters 6 and 7.

4.5.2.2 Basal Clays

Bank exposures and auger hole information reveal the presence of a layer of gleyed grey-clays near the base of some cut banks. These appear to be the product of reducing conditions associated with clay lenses that have been subjected to higher water tables prior to stream incision. The clays appear to have been deposited in former pools and have had sand and gravel deposited over them. With incision and land use changes, water tables have lowered and the basal gravels and clays are now exposed. The gleyed character of these clays (see Figures 4.13 and 4.19) are evidence of a drop in water table associated with bed lowering.

It is noteworthy that some floodplains are more than 8m above the present low flow water mark, well beyond current 1-in-100 year flood levels (see Table 4.9, Appendix 8). Floodplain soils at these locations are youthful unlike those on adjacent terraces that are pedogenically altered, evidence that these channels have recently incised to a level whereby the existing floodplains could become abandoned and cut off from the modern depositional environment.

4.5.2.3 Overbank Fines

The upper unit of silty-sands (widespread floodplain loams) overlying the basal gravels is evidence of widespread overbank deposition. While some of these fines may have been laid down as within-channel benches and oblique accretion deposits over point bars, their sloping topography towards backchannels near the valley margins, and their relationship to a thickening gravel unit towards the channel, suggests that most of their vertical extent represents overbank deposition. In confined reaches, flow constriction and associated turbulence has allowed the finer gravels to be deposited, along with sand and silt in the upper strata of the floodplain (S4, Figure 4.17). During large floods, gravel has probably been transported out of the channel and deposited on to the floodplain, leaving gravel lenses in an otherwise silty floodplain stratigraphy (Figure 4.18).

4.5.2.4 Cohesiveness of Warrell and Deep Creeks

Of particular note is that the floodplains along Warrell Creek and middle and upper Deep Creek are stratigraphically different from those in the remainder of the catchment (Appendix 8). They are formed of cohesive fines that are difficult to penetrate with a hand auger to depths greater than 3 or 4m; within this depth no gravels were detected. Fine gravels are present as bed material and bars in the channels but their absence in the adjacent floodplain alluvium suggests these channels have not exhibited any recent lateral migration. Instead, they appear to have vertically aggraded and built floodplains by overbank accretion while maintaining a gravel bed, in a manner similar to that described by Nanson and Young (1981) for streams in fine-textured alluvium in the Illawarra region of coastal NSW. On Warrell Creek the channel has accreted to such an extent that the terraces on the middle reaches have been buried.

Figure 4.12: Gravel bar formation at T4

Figure 4.13: Floodplain stratigraphy and bank exposure at M4

Figure 4.14: Stratigraphy of a remnant floodplain at S3

Figure 4.15: Cut and fill sequence from a remnant floodplain at D3

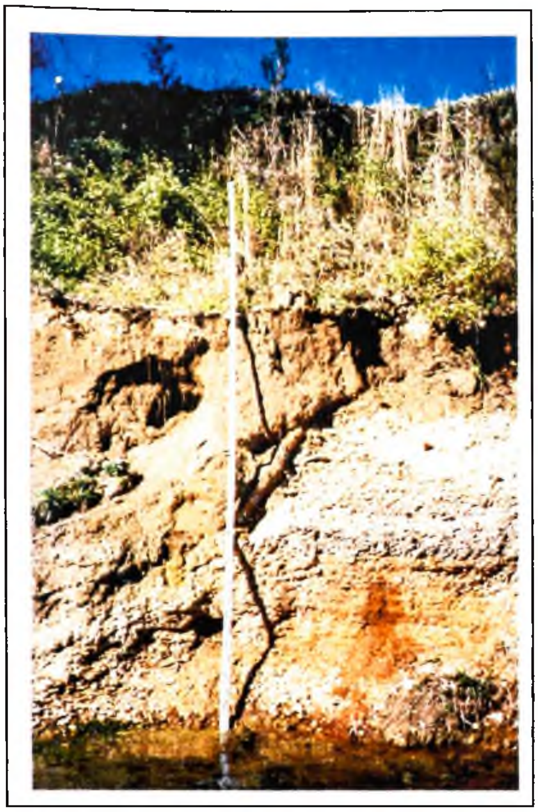


Figure 4.16: Cut and fill sequence from a prior channel avulsion at N4

Figure 4.17: Overbank deposition of a mixed load in a confined reach at S4

Figure 4.18: Gravel lens from overbank deposition of gravel at B2

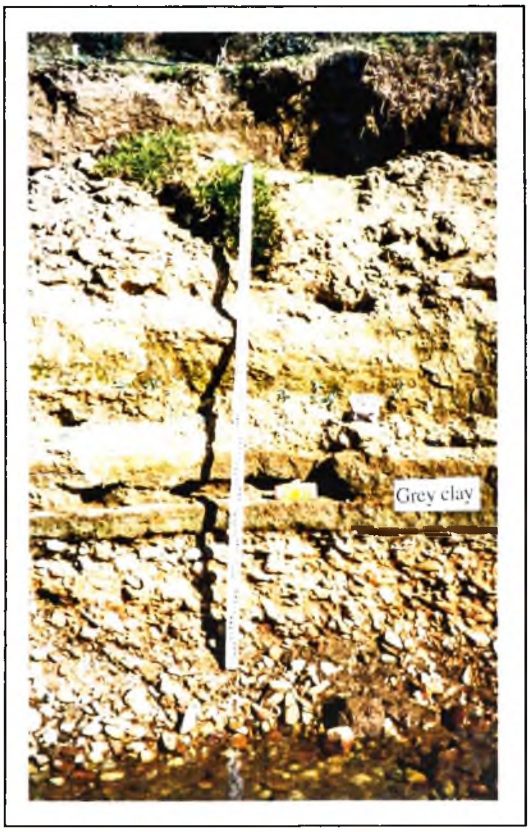


Figure 4.19: Basal gravel exposure after bed and water table lowering at T4

4.5.3 Relationship between Floodplain Gravels and Bed Material

Exposed floodplain basal-gravel units were excavated and sieved in order to compare clast sizes with those from the present streambed (Table 4.13).

Table 4.13: Comparison of floodplain gravel size compared to streambed gravel size
(Figures in bold indicate the areas with higher mean gravel size)

SITE	FLOODPLAIN Mean bedload width (mm)	STREAMBED Mean bedload width (mm)
T2	**22.47**	21.58
T3	**16.73**	15.01
T4	**11.88**	10.70
T5	**9.77**	6.02
T8	6.92	**8.44**
N2	16.62	**17.22**
N4	**15.58**	9.85
N5	**8.82**	6.20
M1	**30.47**	19.42
M2	**16.45**	10.86
M4	10.20	**18.37**
S3	**30.76**	19.41
S4	7.63	**13.46**
S5	7.78	**9.35**
B2	14.24	**17.67**
B3	8.96	**11.54**
D3	7.58	**15.23**

Section 4.4 indicated downstream fining in all of the tributaries except Deep and Warrell Creeks. Sieving of floodplain deposits also reflect this trend. When stream bed and floodplain results are compared, the upper and middle reaches of these creeks reflect that floodplain gravels are generally equal in size to those in the modern channel bed. In just two cases (the uppermost sampled reaches of Missabotti Creek and South Arm; M1 and S3) the floodplain gravels were significantly coarser than adjacent streambed

samples. In Taylors Arm, where five sites were analysed, there is a marked similarity downstream between clast sizes on the channel bed and those from the adjacent floodplain. This suggests that recent erosion and channel widening are providing channel bed material from local floodplain erosion without substantial transport downstream. In contrast, the lower reaches illustrate a tendency for bed-material clasts to be somewhat larger than those found in the adjacent floodplain. This may mean that eroded gravels from the base of adjacent downstream floodplains are being selectively sorted, the sands and granules being washed downstream and the gravels, due to low gradients, were left behind. The sharp downstream decline in sediment size in the upper catchments, and the abrupt lithological transition from schistose and phyllitic sandstone gravel in the upper catchments to almost entirely quartz downstream, indicates the gravel size fractions are only moving short distances downstream and are not being completely flushed through the basin at this stage. This is supported by a trial application of the Ackers and White (1973) sediment transport equation which reveals that only 4 of the 36 sites in the catchment would transport more than 750t/year of bed material, and commonly the amount is much less than this figure (Lyall and Macoun, 1997).

4.5.4 Gravel Transportability

Simple bivariate relationships between slope and sediment size show that gradients in the middle reaches are steep enough to transport bed load of the D_{50} size obtained for locations in these reaches. In summary, upper reaches of the catchment streams have representative surface material D_{50} >50 mm (and sub-surface sample D_{50} >20 mm) on slopes of about 0.004 to 0.005. Despite the steep slopes, the bed material is sufficiently large that it is not readily transported. The middle reaches (eg. N2-N5, T3-T5), however, have surface material D_{50} of 20-40 mm (and sub-surface sample D_{50} 5-15 mm) which is readily transported at gradients of 0.002 to 0.003. In these middle reaches there has been a sizeable reduction in slope compared to the upper reaches, but the reduction in the size of the bed material has been proportionately greater. This relationship means that the bed material is more readily transported at these slopes. By comparison, the lower reaches have further reduced surface D_{50} of 15-30 mm (and sub-surface sample D_{50} 5-13mm) that is not readily transported at the measured gradients of ~0.001. The lack of transport is due to the fact that the decline in slope in the lower reaches has not been matched by the corresponding decrease in grain size.

Even prior to European influences, the middle reaches were probably more prone to geomorphic change compared to the upper and lower (non-tidal) reaches. Extensive floodplains containing stored gravel (all deposited by 2500 years ago – see Chapter 6) of a comparable size to the current bedload suggests that these reaches were actively eroding and depositing coarse sediment.

Deep Creek and Warrell Creek appear to be substantially different to other tributaries in the Nambucca catchment. Their upper and middle reaches have been significantly more stable over a longer period. The narrow floodplains and extensive terraces found in the middle reaches of Deep Creek indicate very little lateral movement since the present regime started. A lack of floodplain-stored gravel in both of these systems would help explain their stability.

4.5.5 Comparative Bank Strengths

Due to the proliferation of bank erosion within the Nambucca catchment, comparative measurements of bank shear strength were carried out using a Genor Field Inspection vane tester. Shear strength of alluvium is only a rough index of soil erodibility by fluvial activity. However, in the absence of more sophisticated technology, it does provide a guide. Fifty tests were conducted at each of 46 different bank exposures encompassing 24 different sites.

Bank substrates were classified into four major groups:

- Clays (grey clays, mottled red/brown clays),
- Clay loam (predominantly silt with some sand),
- Loam (approximately equal proportions of sand and clay), and
- Sandy loam (predominantly sand with some silt).

It was also noted whether or not there were fine gravels in the substrate or if the substrate was covered with grass. These two parameters can affect the shear strength of the bank materials in certain situations. Tabulated results for all the sites are given in Table 4.14.

Table 4.14: Comparative bank strengths for the alluvium in the Nambucca catchment

Site	Bank Substrate	Shear Stress (t/m²)	Grass cover over substrate	Fine gravel in substrate
T2	Clay Loam	2.46 ± 0.64	x	✓
T2	Grey Clay	1.71 ± 0.44	x	x
T2	Loam	1.56 ± 0.42	✓	x
T2	Loam	1.97 ± 0.88	✓	x
T3	Clay Loam	2.46 ± 0.64	x	x
T3	Clay Loam	4.43 ± 1.52	✓	✓
T3	Loam	2.45 ± 0.85	✓	x
T4	Sandy Loam	2.42 ± 0.55	x	x
T4	Grey Clay	2.59 ± 0.70	x	✓
T5	Grey Clay	5.28 ± 1.26	x	✓
T8	Clay Loam	5.01 ± 1.90	x	✓
T10	Clay Loam	2.72 ± 0.67	x	✓
T10	Clay Loam	3.79 ± 1.16	✓	x
N1	Clay Loam	3.53 ± 1.41	x	✓
N2	Clay Loam	4.20 ± 0.99	x	x
N2	Sandy Loam	1.27 ± 0.52	x	x
N2	Sandy Loam	2.08 ± 0.88	x	✓
N4	Clay Loam	8.73 ± 2.01	x	x
N4	Clay Loam	2.19 ± 0.50	✓	x
N5	Sandy Loam	2.57 ± 0.73	x	x
N7	Sandy Loam	1.01 ± 0.34	✓	x
M1	Sandy Loam	2.56 ± 0.52	x	x
M1	Sandy Loam	2.40 ± 0.62	x	x
M2	Loam	4.68 ± 1.43	x	✓
M3	Grey Clay	6.67 ± 1.40	x	x
M3	Loam	3.61 ± 0.94	x	x
M4	Sandy Loam	1.75 ± 0.97	x	x
M4	Loam	5.04 ± 1.96	x	x
S3	Sandy Loam	3.68 ± 0.75	x	✓

Site	Bank Substrate	Shear Stress (t/m^2)	Grass cover over substrate	Fine gravel in substrate
S3	Sandy Loam	4.70 ± 0.77	x	x
S3	Loam	2.34 ± 0.88	✓	x
S4	Sandy Loam	2.80 ± 0.67	x	✓
S4	Clay Loam	2.45 ± 0.67	x	x
S5	Loam	2.38 ± 0.61	x	✓
B2	Sandy Loam	1.78 ± 0.51	x	x
B2	Sandy Loam	4.34 ± 1.01	x	x
B3	Grey Clay	3.21 ± 0.65	x	x
B3	Clay Loam	3.35 ± 0.90	x	x
B3	Sandy Loam	1.62 ± 0.69	✓	x
D2	Loam	4.54 ± 1.21	✓	✓
D3	Clay Loam	4.02 ± 0.37	x	x
D3	Sandy Loam	5.96 ± 1.58	x	x
D3	Mottled Clay	8.65 ± 3.19	x	x
W1	Clay Loam	4.16 ± 2.23	x	x
W3	Clay Loam	3.80 ± 0.87	✓	x
W3	Clay Loam (Cattle Trampled)	11.41 ± 1.10	x	x

The mean values for the different substrates are as follows:

Clays: 4.69±2.66 t/m^2 Clay Loams: 4.29±2.45 t/m^2

Loams: 3.14±1.20 t/m^2 Sandy Loams: 2.73±1.38 t/m^2

The pattern of increasing shear-strength values with increasing silt/clay content found here corresponds with that reported by Schumm (1960). Although the grassed banks appear more stable than the exposed banks, their mean shear-strength was actually lower than that of the exposed banks for each substrate.

The presence of fine gravel dispersed in a fine alluvial matrix appears to have little effect on mean shear-strength values in the Nambucca stream-banks. The major variable controlling bank erosion appears to be the nature of the material at the base of the bank, for once the base is eroded, the strength of the overburden becomes largely irrelevant.

For a number of reasons (most importantly bed lowering), shear vane values for bank material do not closely correlate with the severity of bank erosion visually evident at individual sites (see Figure 4.11 and Figures 4.13 – 4.17). In most cases where erosion of composite banks is occurring, the basal gravels are eroded rendering the more cohesive alluvium above prone to failure by collapse (Thorne and Tovey, 1981). Once this material has collapsed into the channel, becoming fragmented while falling, it is more vulnerable to stream erosion.

From Table 4.14 it is apparent that the average shear strength values for all the stream banks in the catchment, other than Deep Creek and Warrell Creek, are very similar, averaging about 3 tonnes/m^2 (about 4 tonnes/m^2 for Missabotti Creek). Deep Creek and Warrell Creek have significantly higher values (about 6 tonnes/m^2), and this is strongly reflected in their channel and floodplain morphologies. The fact that these two streams do not have fine-gravels that can be eroded from the base of their banks adds to their erosional stability. In combination with the greater shear strength of the overlying fines, this has lead to their distinctive stability and channel geometry.

4.5.6 Gravel Characteristics and Bank Erosion

Similar land use changes have prevailed up and down the catchments of the north coast of NSW. Probably the single most important explanation for the Nambucca's stream channels eroding so severely in response to European settlement is the nature of the basal gravels that underlie most of the floodplains. The relatively fine, well rounded and unweathered quartz gravels in the middle and lower reaches contain almost no cohesive matrix. With the exception of the headwater reaches, the gravels in the floodplains have mean sizes ranging from about 6-16 mm and are almost free of induration. In places they can be scooped from freshly exposed floodplain banks with a bare hand, exhibiting little more cohesion than a group of marbles. Because of the thickness of the gravel layers they were probably exposed, to some extent, at the base of the pre-settlement stream channels but protected by vegetation and woody debris. However, with channel incision they became substantially more exposed and the removal of bank vegetation, and associated protective root mat that held them firmly in place, the rivers have readily entrained the gravels. The importance of native riparian vegetation for holding together such unconsolidated banks has been well documented on other coastal rivers (Raine, 1994) and the lack of such vegetation throughout the Nambucca is a key factor behind the instability of the streams within the catchment.

5. INFLUENCE OF RIPARIAN VEGETATION ON CHANNEL BEHAVIOUR

5.1 Introduction

The role of riparian vegetation in fluvial geomorphology has gained increasing attention in recent years. Riparian vegetation and large woody debris (LWD) in the channel cause resistance to flow, which in turn can reduce bed-load transport rates, and increase bed stability. Vegetation significantly increase bank strength, such that channels having dense and well-structured bank vegetation may be significantly narrower than the same channels without vegetation (Hey and Thorne, 1983; 1984; Ikeda and Izumi, 1990; Millar and Quick, 1993; 1996; Friedman et al., 1996; Huang and Nanson, 1997). However, the extent and nature of the impact of vegetation on flow resistance and bank strength varies with catchment scale. Small streams can be significantly affected by a single large tree growing on the banks whereas the same size tree on a larger river will have an insignificant affect.

Importantly, riparian lands with their fertile alluvial soils were the first areas to be cleared and intensively farmed by early settlers (Brierley et al., 1995). Because riparian vegetation bore the brunt of early settlement an important control on the fluvial system was greatly altered.

5.2 Riparian Vegetation and Fluvial Geomorphology

5.2.1 Early Perceptions

The importance of riparian vegetation as an agent in bank stabilisation were first recognised in Australia by Governor King in 1803. An excerpt from The Sydney Gazette (cited in Raine and Gardiner, 1994, p.15) highlights the perceived problem of removing bank vegetation on the Hawkesbury River:

> "From the improvident method taken by the first settlers on the sides of the Hawkesbury and creeks in cutting down timber and cultivating the bank, many acres of ground have been removed, lands inundated, houses, stacks of wheat, and stock washed away by former floods, which might have been prevented in some measure if

> the trees and other native plants had been suffered to remain, and instead of cutting any down to have planted others to bind the soil of the banks closer, and render them less liable to be carried away by every inconsiderable flood."

Whilst this is not scientifically definitive evidence for the role played by vegetation on bank stabilisation, it provides supplementary support for a good deal of subsequent research which documents the rapidity of channel change and bank erosion following the clearance of riparian vegetation by the first settlers.

Governor King went on to pass an ordinance prohibiting the clearance of vegetation within two rods (10 m) of any river or creek bank. History has unfortunately demonstrated that King's ordinance was not enforced.

5.2.2 Scientific Evidence

There has been a growing number of studies that show the significant role of vegetation as a mechanism for increasing bank strength and controlling channel width (eg. Hey and Thorne, 1983; 1984; Ikeda and Izumi, 1990; Millar and Quick, 1993; 1996). In a study of the effect of vegetation in a glacial melt water stream, Smith (1976) demonstrated that herbaceous plant roots can increase the bank strength by 20,000 times. Mackin (1956), in one of the earliest references implicating the significance of vegetation as a control on bank strength, noted that the Wood River in Idaho had a meandering planform where it flowed through forest and a braided planform where the banks and floodplain were grass.

A further body of literature has addressed the problem of understanding the potential control of vegetation in rivers from a different perspective. In the south west of the USA a number of studies document strong associations between channel narrowing and invasion by *Tamarisk,* an exotic shrub species, on river systems formerly supporting minimal riparian vegetation (Hadley, 1961, Schumm, 1969; Turner, 1974; Burkham, 1972; Burkham, 1976; Graf, 1977). In a similar vein, but in New Zealand, Nevins (1969) documented the rapid alteration of a braided river system to a single thread meandering channel following the introduction of willows into the river system. And in the only Australian study of this kind, Brooks (1994) and Brooks and Brierley (1997; 2000; 2002), demonstrated channel contraction of up to 50% over a 30-year period in the lower Bega

River on the south coast of NSW associated with the introduction of hybrid willows into the channel.

Whilst these studies also demonstrate the large impact that vegetation alone can have on rivers, they also highlight three important points. Firstly, that changes in vegetation composition and structure can fundamentally change river behaviour. Secondly, that channel change associated with vegetation removal will not be inversely proportional to channel change following vegetation introduction. Thirdly, that the mechanisms by which vegetation influences river behaviour are far more complex than simply increasing the bank strength. For example, increasing bank strength in a braided gravel bed river will not necessarily change that system to a single thread meandering channel (Nevins, 1969). Channel contraction must also occur, and for this to occur the vegetation must be capable of colonising within the channel. In so doing the vegetation has the potential to significantly influence a number of other fluvial processes. It can stabilise in-channel sediment deposits, it may induce wash-load deposition (i.e. fine sediment that would otherwise not be deposited), and it can potentially reduce flow velocities.

5.3 Bank Stabilisation

The primary mechanism by which vegetation increases bank strength is through root reinforcement of the bank material, and this is the reason Millar and Quick (1993) utilised the modified friction angle as a means of quantifying the role of bank vegetation. That is, vegetation has the effect of making the bank material appear more cohesive than it actually is. A dense surficial mat of fine roots will be most effective at inhibiting fluvial corrasion of the channel margin (Smith, 1976), whereas coarse deeper roots will reduce the tendency for mass failure, providing they extend below the potential slump failure plane (Abernathy and Rutherfurd, 1996). Coarse roots in isolation will have little impact on reducing the potential for fluvial corrasion. Ideally a bank should have a diverse array of root types, including deep tap roots and fine surficial roots.

An additional riparian vegetation characteristic rarely considered by geomorphologists and river managers is the role played by the roots of trees and shrubs contained within bank slump blocks. Thorne and Tovey (1981) consider the value of a slump block in

lessening the threat of further erosion, but do not recognise the value of the root strength within the block. On well-vegetated banks that are subject to mass failure associated with bed degradation, often the tree and shrub species will keep growing on a slumped block when it has become dislodged from the main bank. The roots will often continue growing and bind the block to the toe of the bank, creating a very effective natural toe revetment feature (Ikeda and Izumi, 1990). In natural forested systems this is undoubtedly an important feature in the channel recovery process following bed instability. Conversely, slump blocks with little vegetation on them can be readily reworked by low flows, quickly negating the toe revetment role played by slump blocks.

5.4 Effects of Riparian Vegetation Clearance

The removal of channel and floodplain vegetation can severely alter the way in which channels and floodplains evolve. The effects of vegetation clearance on a fluvial system includes increases in; discharge, channel width, sediment transport, groundwater level and lateral migration (Schumm, 1969). There is also a corresponding decrease in channel sinuosity, bank stability and floodplain inundation. Further problems include bed level fluctuations, the loss of the pool-riffle sequence and, associated aquatic and terrestrial habitat.

The extent of the hydrological and geomorphic change described above can be dependant upon the following factors:

- Catchment size
- Post-climatic events/changes
- Prevailing climatic environment
- Valley slope
- Type of bed and bank material
- Type of vegetative environment pre-clearance
- Rate of vegetative recovery post-clearance
- Land use practices post-clearance

In Australia, it is easier to find evidence for severely altered environments than in other countries due to the relatively short period of European occupation. Despite this, and a documented record of vegetative composition of some catchments, there is little in the way of evidence describing the rate and extent of channel change in the first half century of post-settlement European occupation in Australian catchments. Until the advent of aerial photographs in the middle of the twentieth century there was no perceived need, nor accurate method, of assessing changes in riparian vegetation cover and channel morphology on catchment-wide basis.

There are studies that have shown that streams with grassed banks are 1.4 to 2.0 times wider than those banks of dense scrub (Hey and Thorne, 1984). Subsequent research (eg. Millar and Quick, 1993; 1996) suggest that grass streams may in fact be three times wider than densely vegetated channels. These studies indicate the importance of dense riparian vegetation and indicate the changes that can occur in channel morphology after riparian zone clearance.

5.5 Role of Woody Debris in Fluvial Geomorphology

In general terms, woody debris can be described as dead vegetation that has fallen into a stream. Wind throw, bank erosion and landslip are common causes of riparian tree-mortality, which result in organic debris entering the channel. When logs enter the channel, this material is described as large woody debris (LWD). It plays an important role maintaining both hydraulic resistance and bed levels (Keller and Swanson, 1989).

Numerous studies have shown the importance LWD has in reducing bedload transport (eg. Keller and Swanson, 1979; Smith et al., 1983; Assani and Petit, 1995), as log jams increase channel roughness and act as sediment traps. The increase in roughness alone means the total shear stress necessary to initiate and maintain the movement of bed material is much higher, requiring a greater discharge to move the bedload (Assani and Petit, 1995; Gurnell et al. 2000). Smith et al. (1993) found that experimental removal of LWD resulted in a dramatic redistribution of bed sediment and changes in bed topography. In addition, the primary flow path was changed, altering the location of bars

and pools (Gurnell et al., 2002). These factors contributed to local bank erosion and channel expansion.

In Australia there has been a concerted effort by river managers to clear streams of LWD (Rankin, 1980). This has been supported by some findings that large organic debris dams, in moderately sized low gradient streams, have been associated with stream bank erosion, in-channel deposition, meander cut-offs and mid-channel bar formation in reaches of channel that may otherwise be meandering (Keller and Swanson, 1979). In a report for the journal of Soil Conservation for New South Wales, Rankin (1980, p.132) states:

> "Objections are often raised to stream clearance operations undertaken by the state government and councils. These works generally consist of the removal from the channel of obstructing trees, both live and dead..... The condition of the stream channel can cause only minor variations in high discharges, which are determined by the rainfall within the catchment. When the flow is blocked by an obstruction the discharge is not reduced. If the water cannot be carried it flows out across the adjacent flats. During low flows, obstructive vegetation within the stream does play an obvious part in reducing velocities by retarding and ponding water. However, this effect becomes less evident during high flows. When the river is in flood, obstructions in the channel generate turbulence and higher localised velocities are required to carry the discharge through a restricted waterway, with consequent erosion of vulnerable banks....one of the most obvious benefits of desnagging and stream clearance is that the removal of obstructions will increase the actual waterway capacity of a congested channel. The discharge in the stream will not be altered. The overall rate of movement of flood flows will not be significantly increased and there will be less turbulence."

The above statement by the principal engineer for river improvement with the (then) New South Wales Water Resources Commission indicates the rationale behind river improvements at the time. Although there is an awareness of the problem of in-stream vegetation growth and the erosional threat poised by a single fallen tree, there is a distinct lack of appreciation or understanding of the value of LWD in increasing channel roughness (eg. Manning's n) and stabilising the channel bed. These statements also fail

to recognise the erosional problems from increased discharge and velocity associated with increasing channel capacities. Rankin also fails to acknowledge the effects of catchment scale or human influences compounding the effect of removing LWD.

The effect of flow deflection and erosion from a fallen tree is only a symptom of other problems. These problems include discontinuous riparian vegetation, bed lowering (particularly on gravel bed streams) and increased stream velocity. The stance on de-snagging also disregarded the ecological value of LWD and its importance in the pool/riffle sequence (Keller and Swanson, 1979) given a wide variety of in-stream flora and fauna utilise woody debris as habitat (Gurnell et al., 1995).

The effect of LWD on hydraulic resistance decreases with catchment scale (Brooks et al., 1997). In low order streams the height of the fallen trees will generally be greater than channel width allowing logs to remain as they fall, often for hundreds of years (Featherstone et al., 1995) or even thousands of years (Nanson et al., 1995). The logs often fall perpendicular to flow resulting in maximum resistance to flow - except for the highest order and narrowest streams where the logs are held completely above the channel giving little or no resistance (Swanson and Nakamura, 1993). Further downstream in lower order channels the stream is generally wider than the length of the fallen trees. This allows LWD to be aligned parallel to the flow hence blockages are minimised, but the potential to assist point bar accretion and protect the toe of the bank is maximised (Nanson, 1980). In this situation, larger compound jams can form downstream. However, human interference has meant that log jams often decrease in size downstream from forested headwaters to disturbed agricultural floodplains as in Jones Creek in Victoria, southeastern Australia (Cohen et al., 1996; Cohen, 1997).

Brooks et al. (2002) re-introduced LWD into the Williams River on the mid-north coast of NSW through the placement of 430 logs along an 1100 m sample reach. After three years, and six flows above that of a mean annual flood, there is evidence emerging that the geomorphic variability of the reach has substantially increased, with a pool-riffle sequence becoming evident in the sample reach.

5.6 Vegetation and Human Impacts on NSW Coastal Rivers

Native riparian vegetation bore the brunt of change associated with post-settlement land use practices, the result impacting river behaviour over the next 150- 200 years. This is in contrast to what is currently known about river-channel change from the experience of land use changes in Europe over a much larger timescale that forms the basis of much of the current geomorphic literature.

5.6.1 The Impact of Post-Settlement Land Use - Conventional View

The extent to which post-settlement vegetation clearance and subsequent land-use has altered the form and behaviour of NSW coastal rivers is a contentious issue among the small group of researchers who have considered the issue. Until recently the accepted interpretation amongst the local fluvial geomorphology community has been that it is our extreme climatic variability that is principally responsible for the dynamic behaviour of many of coastal rivers, particularly throughout this century and in some cases over the later part of last century (eg. Pickup, 1976; Henry, 1977; Erskine and Bell, 1982; Erskine, 1986; Warner, 1987; Warner, 1992; Warner, 1995). Post-settlement clearance and riparian land use were seen to be relatively minor contributing factors superimposed on this 'natural' instability (Erskine and Warner, 1988). In effect these studies imply climate forcing dominates morphological change in coastal rivers. This view was given added weight by the development of a hypothesis that proposed NSW coastal rivers are subject to fluctuating climatic regimes known as flood and drought dominated regimes (FDRs and DDRs) (Warner, 1987; Erskine and Warner, 1988). These regimes were thought to alternate roughly on a 50 year cycle, and to be responsible for many morphological peculiarities of these rivers.

5.6.2 An Alternative View

The fact that there is extreme climatic variability in eastern Australia has been clearly demonstrated by Finlayson and McMahon (1988), amongst others, and is not disputed. However, the argument that due to this climatic variability, historically documented river behaviour is representative of longer term behaviour (i.e. over the last few thousand years), has recently been questioned (Raine and Gardiner, 1994; Brooks and Brierley, 1997; Brooks and Brierley, 2000). Brooks (1994) and Brooks and Brierley (1997),

accepted the existence of FDR/DDR regimes, but found that massive sedimentation associated with post-settlement disturbance in the Bega catchment (NSW South Coast), and willow colonisation within the channel, induced morphological changes that were largely out-of-phase with morphological responses that would be expected by the FDR/DDR theory.

Recent critiques of the FDR/DDR concept (Brizga et al., 1993; Kirkup et al., 1998) raise serious questions from a statistical and climatological perspective as to the validity of ~50 year alternating cycles. Kirkup et al. (1998) highlight significant problems with the data sets from which the *alternating* regime hypothesis was derived. They do not dispute that a major climatic shift occurred around the late 1940's or early 1950's. However, they suggest the evidence for alternating regimes of flood and drought up to several decades in length is highly equivocal. Kirkup et al. (1998) also take issue with the way the FDR/DDR regimes have been extrapolated from the Hawkesbury/Nepean system, where the hypothesis was first derived, to other catchments around NSW, with little regard for the global and regional scale climatic phenomena that must be driving such regimes. The studies by Brizga et al. (1993), Brooks (1994), Brooks and Brierley (1997), Kirkup (1996) and Kirkup et al. (1998) have suggested that shorter climatic cycles in the order of the 5 to 7 year cycles associated with the El Nino Southern Oscillation (ENSO) are probably of much greater importance to river behaviour than is a 50 year (or multi-decadal) cycle.

The climate forcing theory of recent river channel changes also rests uneasily with a large number of studies that have documented dramatic changes in river behaviour post-settlement (eg. Pickup, 1976; Eyles, 1977; Henry, 1977; Erskine and Bell, 1982; Erskine, 1986;Prosser, 1991; Prosser et al., 1994; Murn, 1995; Burston and Good, 1996; Brooks and Brierley, 1997). In many cases, such behaviour appears to be beyond the scale of river behaviour over the previous 5000 - 6000 years, as inferred from the sedimentary record. (eg. Eyles, 1977; CSIRO, 1993; Prosser, 1991; Prosser et al., 1994; Brooks and Brierley, 1997). This being the case, recent work has sought to reassess the extent to which post-settlement disturbance of catchments, in particular disturbance of the riparian zone, have primed many rivers for dramatic changes in form and behaviour.

In light of these points it is suggested that the clearance of riparian vegetation and the subsequent disturbance of riparian land associated with agriculture, had the potential to profoundly change river channel function. This is not to say there was always a catastrophic response to vegetation clearance. Due to a range of local factors, some rivers are more sensitive to disturbance than others. What we must consider is that riparian vegetation change increased the likelihood of major channel destabilisation.

5.6.3 Lagged Responses and the Role of Vegetation

A great deal of work still remains to be done before the extent of change to rivers wrought by post-settlement activity can be firmly established. To some river managers there may be a feeling that 'what's done is done and does it really matter if it is all the fault of the early settlers?' From a geomorphic and river management perspective it is crucial that this question be settled, as many of the changes imposed on rivers since European settlement are still being felt today and repairing the damage requires a detailed understanding of the cause. Lagged responses well in excess of 100 years are a common phenomenon in geomorphology (Chappell, 1983). Indeed lags of this order of magnitude have probably been in effect in the Nambucca catchment. The question of how vegetation can best be used in river management in part rests on our coming to terms with what happened when native riparian vegetation was originally removed.

5.6.4 The Potential for River Instability

Understanding the potential for river-channel instability is a crucial precursor to understanding the role of vegetation. Rutherfurd et al. (2000) came up with a first approximation of a river stability index, which included the valley slope and the coefficient of flood variability. With further development to include additional factors such as bank and floodplain material, and the degree of valley confinement, this approach may provide a very useful indicator of the potential for river instability, and the role of vegetation. Incorporated with this kind of analysis must be the bank erosion process analysis outlined by Millar and Quick (1993).

5.7 The Pre-European Riparian Vegetation of the Nambucca Catchment

5.7.1 Evidence for Vegetation Composition on Other NSW Coastal Rivers

The most comprehensive review of the likely composition of pre-settlement riparian vegetation along NSW coastal rivers is contained within a report compiled by Raine and Gardiner (1994) of the then NSW Department of Water Resources. Much of the historical evidence they present comes from the lower Hunter River, but they also cite a number of references that indicate similarities between the nature of riparian vegetation on the Manning and Nambucca Rivers, as well as Taylors Arm (Raine and Gardiner, 1994, p40, 79). The evidence they present suggests all the rivers north from the Hunter, contained extensive stands of dense lowland sub-tropical rainforest, much of which originally contained the highly prized red cedar (*Toona australis*). Some of the accounts they quote are worth repeating to provide some idea of the nature of this vegetation.

> "This scrub, sometimes so thick it was difficult to penetrate even a few yards, extended to the waters edge. Many of the trees were gigantic, and lichens, staghorns, elkhorns and mistletoe flourished" - Breton 1833: p.122 cited in Raine and Gardiner, 1994, p.27.

Perhaps one of the most detailed descriptions of the riparian vegetation comes from George White who, in 1833, described the 'brush' on the northern bank of the Hunter:

> "The northern bank of the Hunter from Lorn downward was lined with jungle or brush almost impenetrable, and to form a road from the Government township site (East Maitland) towards the Patterson River it would be necessary to cut through the brush for 2 or 3 miles from the Hunter River crossing.
>
> Before the axemen came, giant red cedar and fig trees bore their boles upward through the interspersed myrtle and other softwood brush trees and interlacing climbers, crowing all with their wide-spreading leafy heads. Within the outer tangle of "Bolwarra vines", clematis and other climbers, and shrubby plants of the rainforest, a man could in many places walk erect beneath the thick green roof of leaves in the cedar brush. There the light was subdued, and the sun never shone on the thick mat of decaying leaves and mould.

> On this ground and on dead wood were strange fungous growths. Tree-ferns flourished, and smaller ferns vied with mosses on shaded bark ground. Staghorns and elkhorns hugged tree trunks and mistletoe hung heavily from boughs. Overhead, where the fetid acre wide camps of flying foxes were, dense multitudes of the great fruit bats spent undisturbed days in sleep, hanging like large loathsome leaves from the high branches.
>
> On the river banks and the outskirts of the brush, tall smooth-trunked gum trees stretched skyward to the sunlight, and swamp oaks grew near the water. Tall rushes edged the river and the lagoons". (cited in Raine and Gardiner, 1994, p.29)

The existence of a cedar getting (logging) industry along virtually all NSW coastal rivers in the nineteenth century provides additional circumstantial evidence for the existence of vast stands of rainforest along these rivers. Gaddes (1990) indicates cedar logging was practised along every coastal river north of the Shoalhaven catchment in the early decades of the colony. The cedar industry was one of the mainstays of the economy in the early days of the colony, bringing in the first export dollars to the struggling settlers (Hughes, 1984). The industry commenced on the Hawkesbury River in 1790, then proceeded to the Hunter and its lower tributaries from 1801; the Shoalhaven (the southernmost occurrence of cedar) from 1811, the Hastings from 1823, the Manning from 1828, continuing to the 1840's, the Macleay from the early 1830's, the Clarence from 1835 until the mid 1850's, Paterson and Williams Rivers from the late 1830's, the Nambucca, from 1842, the Bellinger, from 1842 continuing to the 1870's, the Tweed River from the 1860's, and the headwaters of the Hunter in the late 1860's.

Gaddes then indicates that:

> "By 1890 the cedar industry, after 100 years, was finished. The easily accessible areas had all been logged over, and much had been destroyed by the agriculture that followed." (Gaddes, 1990, p14)

Gaddes (1990, p16) accounts of the vegetation associated with cedar forest provides a better description of the density of the vegetation and his accounts are all the more pertinent given that he was a third generation 'cedar getter' from the Nambucca area.

> "The red cedar is essentially a rainforest tree, requiring plenty of moisture and rich soil. The early cutters found it growing in great abundance along the river flats. I have never found cedar growing in a gully with no water, so the first thing I looked for was a perennial water course; having found one, I could be confident of finding red cedar growing along its valley."

He goes on to further describe the forest in which red cedar grows:

> "The red cedars domain is the rainforest (better known to the bushman as the black scrub)". ... "The bane of the road-cutter was the vine. Everywhere one moved in the high black scrubs, where the cedars grew, one met with an almost impenetrable entanglement of a great variety of vine species. They included the wire vine (I am calling them by their common names only), which was just as tough as the name implies, through 'wait-a-whiles', billy goat (poisonous), wild grape (watervine) and the never to be forgotten wild strawberry vine. This latter vine was especially designed by nature to separate the bushmen from the bushboys. It grew up to 30 feet high, in dense clumps (with not enough room in them for a tom-tit to chirp). These sometimes covered acres in area and bristled with thorns, resembling the spurs of a game fighting cock, but thrice as dangerous, any encounter with which was guaranteed to let plenty of blood."

This account is based on Gaddes' own experience in the first half of the twentieth century and most likely describes the rainforest conditions further up the valleys (as most of the lowland rainforest would have been cleared prior to this time). Similar conditions would appear to have prevailed earlier in the lowlands.

5.7.2 Pre-European Riparian Vegetation in the Nambucca Catchment

Historical descriptions of the pre-existing riparian vegetation along the Nambucca are scant and lack detail. The few sources that are available can, however, give us a good indication of the riparian vegetation community structure, which, when combined with observed remnant and regrowth species composition, can give a reasonably good idea of what pre-European conditions were like along the banks and floodplain of the Nambucca and its tributaries.

Townsend (1993) in her book on the European settlement of the Nambucca reflects on the vegetation confronting the initial settlers:

> "Although it was to become a rich source of timber with its rosewood, mahogany and especially its red cedar, the Nambucca confronted European settlers with the immediate problem of clearing the land. Eucalypt forest dominated the less fertile uplands. Blackbutt grew to massive proportions and spotted, grey and red gums were common. Beneath these large trees were smaller trees such as river oaks. In the upper reaches of the valley, tussock grass flourished but kangaroo grass was common at lower levels, especially on the coastal margin." (Townsend 1993, p.5)

Gaddes (1990) provides further indication of the extent of rainforest vegetation along the Nambucca floodplain. Specific references are made to cedar having been taken from Taylors Arm, South Arm, Buckra Bendinni Creek, North Arm, and Warrell Creek. The forest lining these streams was invariably described as the dense 'black scrub' described above. Gaddes (p.16) also highlights the relative quality of Nambucca and Bellinger cedar compared to cedar from other coastal rivers.

> "Cedar is very light and one of our few native trees that will float in water. This quality was taken advantage of by the early cedar cutter; however, much of the Nambucca and Bellinger cedar was of such high quality that its denseness barely allowed it to float. I recall the late Stanley Boulton telling me that he once watched my father, the late James Gaddes, fall a cedar tree on the banks of the Nambucca River. As he chopped, some of the chips fell into the water and sank; when the tree fell, and the log was rolled into the river, it promptly sank to the bottom. Such was the quality of the timber in that particular tree - a rather common occurrence on both the Nambucca and Bellinger Rivers".

This gives some indication of the propensity of large cedar logs to sink to the bottom once in the river and act as bed level controls. Gaddes also makes the point that the majority of Australian timbers do not float.

5.7.2.1 Other Evidence

Further evidence for the pre-existence of extensive rainforest on the Nambucca comes from logs that are fairly frequently dug up by gravel extractors both in the current channel and from old channel deposits in the floodplain. Red cedar, rosewood (*Dysoxylum fraserianum*), eucalypts and river oaks have all been found in this manner (R. McWilliam, pers. comm. 13/5/96).

5.7.2.2 River Oaks (*Casuarina cunninghamiana*)

From the historical sources reviewed, only two references are made to the presence of oaks, both of which are from the Hunter. In one quotation above (White, 1833; cited by Raine and Gardner, 1994), swamp oak is specifically mentioned, so these probably relate to *Casuarina glauca*. The other reference (cited in Raine and Gardiner; 1994) describes oaks on a channel island, which may have been the river oak (*Casuarina cunninghamiana*). Townsend (1993) mentions river oaks being among a group of forest trees in the Nambucca region but the populations of river oak were classified as minor compared to the dominant rainforest species and eucalypt woodland species..

Without detailed historic accounts the distribution and extent of river oaks within the Nambucca can only be inferred. The present day abundance of river oaks in most tributaries of the Nambucca indicates they must have existed as a component of the pre-existing "black scrub" although probably not in the same numbers existing in some locations today. Elsewhere in southeastern Australia studies indicate that river oak populations have declined as a result of anthropogenic influences (Kershaw et al., 1994; Gale and Pisanu, 2001). Examinations of the Hunter catchment to the south and the New England Tablelands to the west of the Nambucca indicate that the influx of casuarinas into the Nambucca catchment is against the trend evident in the southeast Australian region. Despite this, localised climatic and anthropogenic factors, and the colonising charateristics of these trees, have resulted in a reversal of the regional trend.

As outlined by Raine (1994), in ecological terms river oaks are an opportunistic primary coloniser requiring relatively high light levels, good access to water and a freshly bared seed bed in order to colonise. At present these conditions are much more prevalent than

they were under the pre-settlement conditions in the Nambucca - hence the current proliferation of river oaks. However, from time to time such conditions must have prevailed locally due to fire or flood clearance of the banks or floodplain, allowing for ongoing river oak survival.

The mono-cultural primary colonisation by river oaks evident today has, in all likelihood, also occurred in the past when gravel bars were exposed following floods. Evidence for this type of colonisation can be seen today on the relatively pristine upper reaches of the Tuross River, on the NSW South Coast (Brooks, pers. comm.).

5.8 Long-term Evolution of Nambucca River in the Context of Pre-European Riparian Vegetation.

In keeping with the debate surrounding the extent to which clearance of riparian lands subsequently affected the morphology and behaviour of coastal rivers, there is little consensus as to what the NSW coastal rivers were like before European settlement. There are a number of additional reasons why this is the case:

- Few researchers have seriously considered the effect that post-settlement clearance of vegetation had on rivers.
- Detailed historical evidence does not exist, making it very difficult to make conclusive claims.
- Geomorphic evidence has often been destroyed by subsequent river adjustments.
- Available geomorphic and sedimentary evidence is only now being collected and interpreted to provide an understanding of rates and processes.
- Very few analogues of pristine alluvial rivers and associated riparian rainforest exist that can be used to infer the likely prior character of currently degraded rivers.

In light of these problems, and due to the fact that detailed field based evidence is not yet available, the following assessment of the likely character of the river is the author's interpretation drawn on a number of information sources:

- The evidence presented from elsewhere regarding the interactions between riparian vegetation and fluvial geomorphology.
- The picture of the pre-existing vegetation structure established in Section 5.7.
- Research from what is probably the last remaining alluvial coastal river in Eastern Australia outside the tropics that has retained its original riparian vegetation cover and woody debris load (Brooks, 1999; Brooks and Brierley, 2002). Whilst this river is in East Gippsland, Victoria, the river retains significant stands of lowland warm temperate rainforest, and includes some of the same species found in the Nambucca - namely: watergum *Tristaniopsis laurina*, lilly pilly *Acmena smithii*, blueberry ash *Elaeocarpus reticulatis*, Blackwood *Acacia melanoxylon*, Pittosporum *Pittosporum undulatum*, and *Notolea* spp. amongst many others, as well as many tree ferns, ground ferns and vine species (Brooks, 1999; Brooks and Brierley, 2001).
- Historical data from before the 1950's can give some clues, however any evidence of channel condition after floodplain clearance must be viewed with caution, as it is likely that significant changes transpired between the commencement of agriculture in the valley and historical evidence originating from early this century.

5.9 Pre-European Channel Condition

5.9.1 Woody Debris.

In general terms, there would have been much higher volumes of LWD in the pre-existing channels of the Nambucca catchment, than the current channels. Due to the inferred smaller channel capacities prior to European disturbance, the relative influence of this LWD on channel processes would have been significantly greater than a simple ratio of pre-European LWD volume to contemporary LWD volume. Following are some specific comments regarding the likely composition of LWD in the Nambucca catchment:

- The longer-term species composition of woody debris will be strongly biased towards species that do not readily decay once they fall into the river. In the Nambucca the most resilient species would appear to be: red cedar, rosewood, Eucalyptus spp (probably mostly *Eucalyptus grandis*), and to a lesser extent river

oak. These species also tended to be the large rainforest canopy species, and many fell not as a result of bank erosion, but by wind throw.

- Many of the other riparian rainforest species, such as, lilly pilly (*Acmena smithii*), weeping myrtle (*Waterhousia floribunda*), blue quandong, (*Elaeocarpus grandis*), blackwood (*Acacia melanoxylon*) and to a lesser extent water gum (*Tristaniopsis laurina*), were more subject to decay, and hence do not comprise a large proportion of the long term store of woody debris. This is not to say that in pre-European times they were not an important component of the woody debris biomass - it is just that there are no examples of these timbers in the river today because there has been 150 years with virtually no recruitment of large specimens of these species.

- As this second group of species are relatively small trees and shrubs, the main way they would be recruited to the stream was through bank erosion. Because many of these species were very effective at minimising bank erosion, recruitment of such species would be highly localised, and fairly slow. Consequently it was probably wind thrown specimens from the first group of trees that made up the largest component of woody debris.

5.9.2 Inferred Pre-Settlement Channel Conditions in each Tributary

The inferences made regarding the possible condition of the pre-settlement channel are based on historic accounts, theoretical knowledge regarding vegetation interactions in rivers, and, what is known about the likely composition of the pre-settlement vegetation community, and to a limited extent, the 1942 aerial photographs. A summary of the general pattern can be seen in Table 5.1.

Table 5.1: Inferred pre-settlement conditions for reaches of the Nambucca catchment from 1942 aerial photograph analysis

Reach	Inferred Pre-Settlement Condition
Upper Alluvial Reaches Sites: M1, N1, N2, S1, S2, T1, T2.	- Channels substantially narrower than at present (at least 50%). - Bank height not that different to 1942 condition, probably slightly less than present condition. - Woody debris occupies a large proportion of channel cross-sectional area (possibly up to 50%). - Woody debris relatively evenly dispersed, with a high proportion of logs remaining *in situ* as they fell - many roughly perpendicular to the flow. Such logs form effective bed-level control. - Bed form variability much greater than today - higher riffles, deeper pools and more of them - Bed-load throughput negligible due to bed armouring woody debris stabilisation and possibly aquatic weeds. - Lateral activity of channel probably up to an order of magnitude less than at present. - Channel avulsion may be a common process in less confined reaches, whereas in more confined reaches localised expansion and contraction will be the dominant form of lateral instability. - Perennial flow - very rarely ceased to flow. - South Arm and Taylors Arm bed-load transport probably even less than North Arm and Missabotti due to better bed armouring (less quartz fraction in gravels). - Lateral channel activity would also have been less on South Arm and Taylors Arm due to greater bedrock confinement.
Middle Alluvial Reaches Sites: M2, M3, N3, S3, S4.	- Channels substantially narrower than at present. - Bank height not that different to 1942 condition, probably slightly less than present condition - sub-critical. - Woody debris still occupies a large proportion of channel cross-sectional area, although less than upstream. Still plays an important role in bed level control, but less than upstream in terms of hydraulic roughness. Localised bank scour associated with logjams possible. - Bed form variability much greater than today - higher riffles, deeper pools and more of them. - Bed-load throughput slightly higher than upstream due to less bed armouring but woody debris stabilisation probably still very important. - Rates of lateral activity of channel probably slightly higher than upstream, but still order of magnitude less than at present. - Meander cut-offs locally more significant - i.e. in the less confined reaches, which are more prevalent in these middle reaches. - Perennial flow - very rarely ceased to flow. - South Arm bed-load transport less than the other two systems, again due to less quartz gravel fraction. Lateral activity also less. - Channel avulsion and expansion also locally significant.
Lower Alluvial Reaches Sites: M4, N4, N5, N6, T4-T8.	- Channels narrower than at present, although, less so than upstream. - Mean bank height not that different to 1942 condition. - Bank height may have been such that dominant erosion processes were transitional (i.e. corrasion and mass failure were both important erosion process - *cf* today where mass failure dominates). - Banks generally well graded and well vegetated, as such; mass failure would have been rare and isolated to actively eroding outside bends. - Large point bars and inset benches present - often well vegetated and relatively stable.

	- Woody debris occupies a lesser proportion of channel cross-sectional area (may be only as much as 10 -20%) . Still plays an important role in bed level control, but less than upstream in terms of hydraulic roughness. Localised bank scour associated with log jams possible. - More logs swept around parallel to flow, providing toe protection. - Bed form variability again much greater than today - higher riffles, deeper pools and more of them - Bed-load throughput slightly higher than upstream due to less bed armouring but woody debris stabilisation probably still very important. - Rates of lateral activity of channel lower than middle reaches. - Meander cut-offs locally significant -but not widespread. - Local channel expansion and contraction probably more important here, possibly associated with logjams. - Perennial flow - almost never ceased to flow.
Mid Buckra Bendinni Creek Site: B2	- Low capacity channel separating large bedrock control scour pools. - Bank erosion, corrasion dominated. - Rainforest vegetation may have encroached into the channel in the low capacity reaches between scour pools. - The majority of woody debris would have been of wind throw origin. - Lateral erosion limited to rare extreme events due to extreme vegetation control. - Bed level variation may not have been dissimilar to the 1942 condition.
Lower Buckra Bendinni Creek Sites: B3, S5.	- Highly sinuous, well-defined channel, meandering through a relatively broad floodplain. - Lateral channel activity dominated by meander migration and cut-offs. - Undercut banks may have been common, held up by dense rainforest root mat. - Bank height sub-critical and hence corrasion dominated. - Woody debris load in the channel would have been extreme and would have had a high proportion of sub-canopy species of fluvial erosion origin. - Channel width much less than canopy height, hence evenly distributed debris and few large jams. - Perennial flow, with some deep pools.
Lower Taylors Arm Sites: T9, T10, T11.	- Extensively bedrock controlled - both laterally (valley confinement) and on the bed. Under these conditions vegetation exerts relatively little control on gross channel morphology. - Gross channel morphology not that different to the present condition. - Pools spacing and depth largely bedrock controlled, so pool riffle spacing similar to the present. - Pools deeper than at present (i.e. due to recent in-filling by bed-load released from middle reaches upstream) - Light suppression due to dense rainforest canopy on both banks probably meant there was less vegetation in the channel than at present. - Large log jams may have formed in this part of the channel from time to time. These may have led to localised bank/floodplain scour, particularly if catastrophic failure occurred.
Warrell Creek and Deep Creek Sites: W1-W3, D1-D3.	- Channel widths similar to the present condition. - Bed level variation marginally higher (i.e. deeper pools and possibly higher riffles). - Woody debris levels higher, with a greater proportion of wind thrown origin. - Lateral channel instability fairly negligible, with the exception of some parts of lower Deep Creek where localised meander cut-offs may have occurred.

5.10 Vegetation Changes and River Degradation

Many long term residents of the Nambucca catchment have observed an increase in the extent of riparian vegetation over the past 50 years, and at the same time have witnessed major increases in channel instability. Some have drawn the conclusion that increased riparian vegetation (predominantly river oaks often growing on bars in the channel) has caused deflection of flow into the banks and contributed to the gross channel instability currently evident (see Appendix 2).

In Chapters 7 and 8 it is suggested that the underlying cause of river instability, particularly in North Arm and Missabotti Creek, is systemic bed degradation. In this section aerial photograph evidence is reviewed for an increase in the extent of vegetation along all tributaries.

5.10.1 Evidence for Increased Riparian Vegetation Since 1950.

The aerial photo evidence presented in Figures 5.1 and 5.2 clearly support the anecdotal evidence that in many sections of the Nambucca catchment there has been a significant increase in the extent of riparian vegetation in the form of exotic and native trees and shrubs. However, the general trend is by no means universal throughout all tributaries. In this context, riparian vegetation is defined as shrub and tree regrowth, consisting of both native and exotic species. Aerial photo interpretation does not allow us to determine the species composition, but it is a safe assumption that species composition in 2003 is not that different to what the situation was in 1991.

There are very few sections of channel where long continuous reaches have become colonised by vegetation. The general pattern appears to be fairly extensive increases at discrete locations, or an increase in scattered trees and shrubs over greater areas.

From the evidence displayed in Figures 5.1 and 5.2 the following conclusions are made about riparian vegetation changes between 1942 and 1991. It must be stressed that these observations represent gross changes. In addition, at some locations the overall extent of vegetation cover may not have changed much over the time period assessed, but the community composition may have changed substantially. This trend would be

more prevalent in those reaches with semi-intact rainforest associations where exotic species like camphor laurel may have displaced native species.

5.10.2 Riparian Vegetation Changes Between 1942 - 1991

Analysis of 1942 and 1991 aerial photographs across the catchment indicate areas of significant increases in vegetation density on the floodplains and ridges. The major reason for the increases of riverine vegetation is due to the dramatic increases in the number of river oaks in the catchment. Not all of the catchment underwent such extensive increases in vegetative cover. Figures 5.1 and 5.2 highlights the changes over time for each tributary. The record of change for each tributary is in Table 5.2.

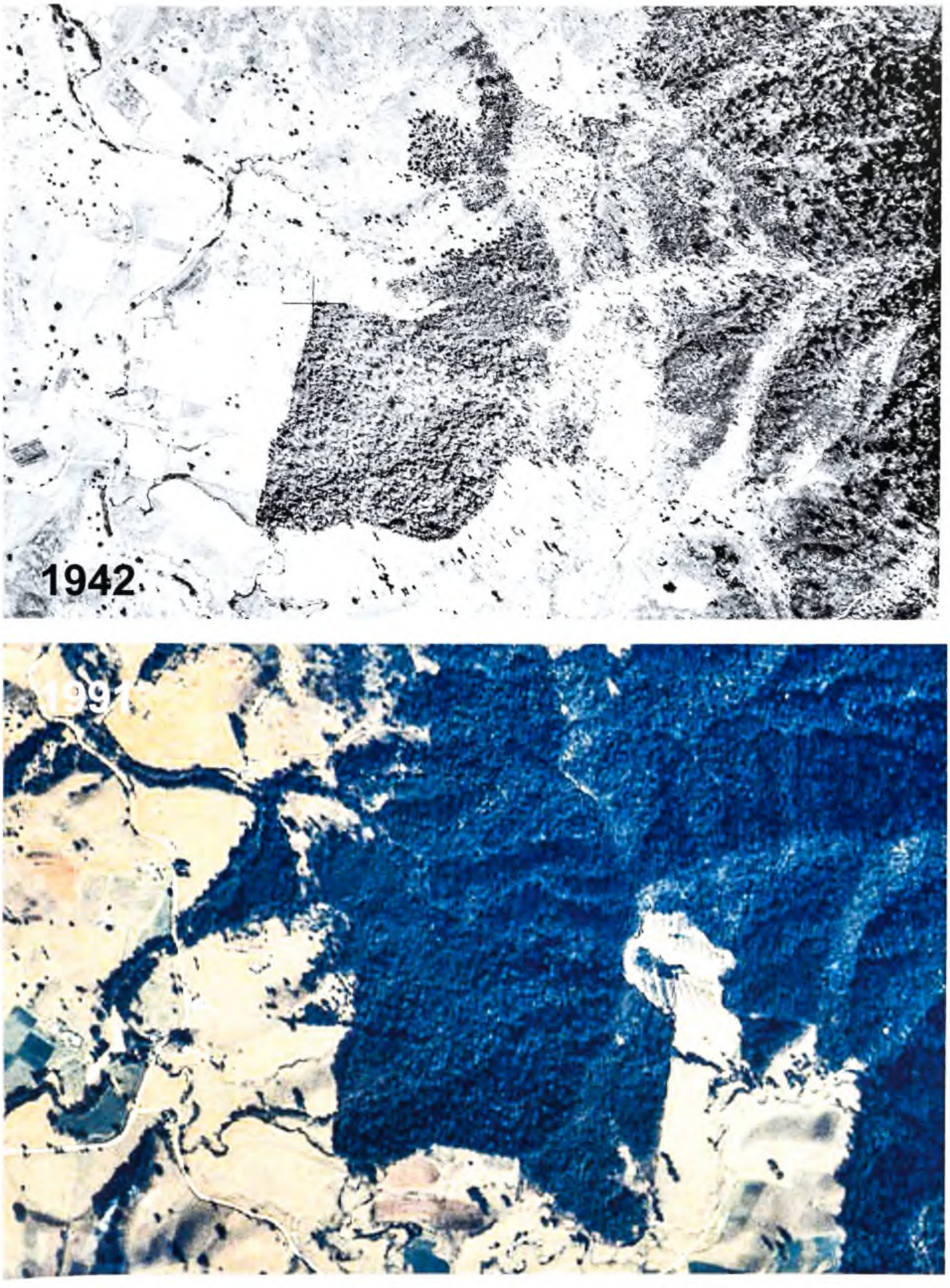


Figure 5.1: Vegetation changes on Missabotti Creek from 1942-1991
(Note: Vegetation density has increased on hillslopes and along watercourses).

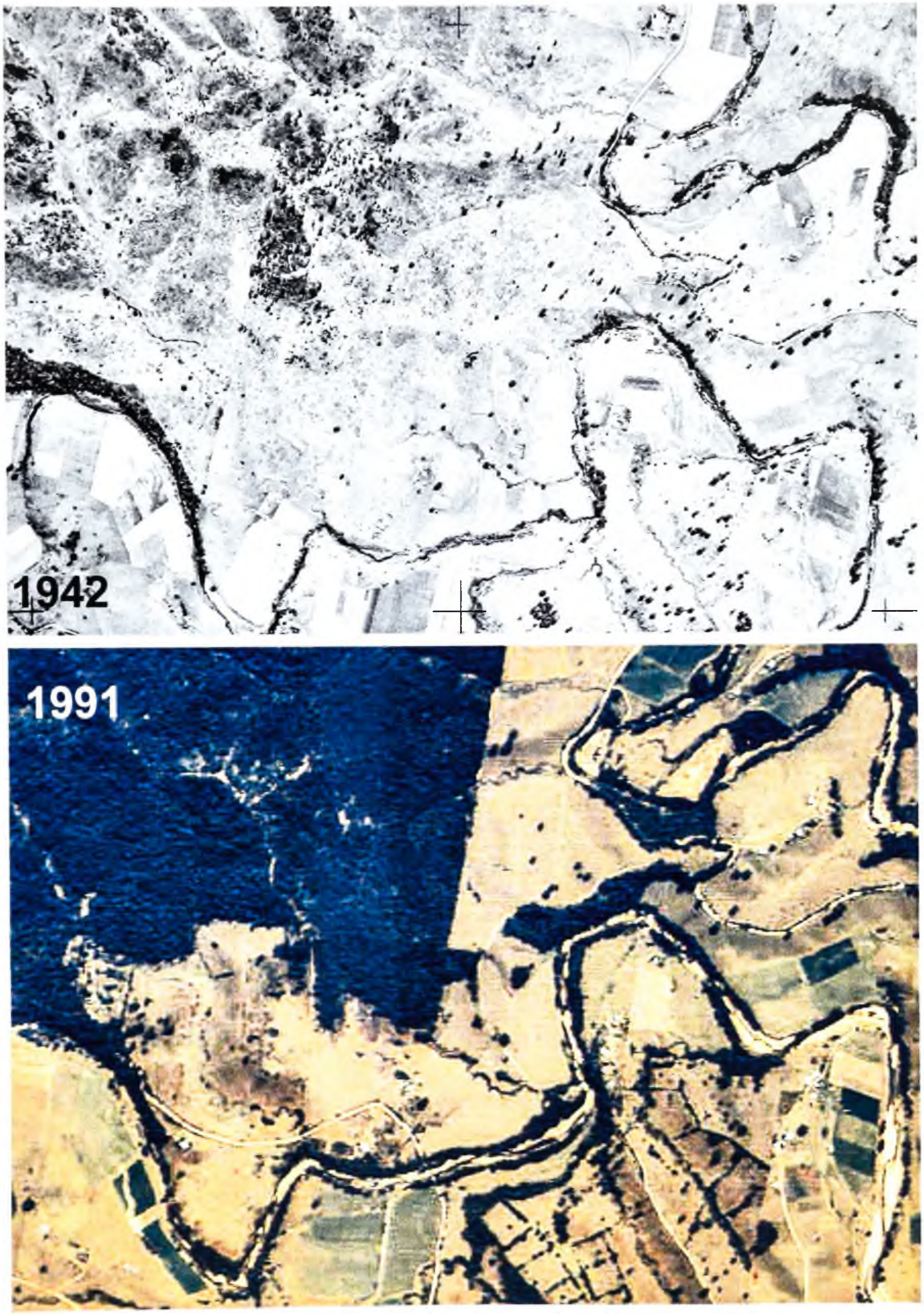


Figure 5.2: Vegetation changes on North Arm near Site N5 from 1942-1991
(Note: Vegetation density has increased on hillslopes and along watercourses).

Table 5.2: Inferred changes in vegetation from 1942-1991

Reach	Inferred Change
Upper Missabotti Ck (M1)	Significant increase but not continuous - predominantly river oaks
Middle Missabotti Ck (M2,M3)	Significant increases, including a fairly continuous reach over a few km above Site M2. Canopy predominantly river oaks, but a range of exotics and natives form a substantial mid-storey here.
Lower Missabotti Ck (M4)	Major increases in some reaches and dramatic decreases in other reaches. Predominantly river oaks on banks and in channel and significant tea tree population in channel.
Upper North Arm (N1, N2)	Only minor build up at discrete locations - predominantly river oaks.
Middle North Arm (N3)	Substantial increases in some reaches and decreases in others. Greater channel instability evident in areas without vegetation than those with.
Lower North Arm (N4 - N6).	Reasonably widespread increases - predominantly river oaks.
Middle Buckra Bendinni Creek (B2)	Little change in overall extent of riparian vegetation.
Lower Buckra Bendinni Creek (B3)	Vegetation increased in lowest reaches - just above South Arm confluence. No change in vegetation extent in some reaches, and a decrease in others.
Upper South Arm (S1, S2).	More vegetation at select sites, but not a uniform increase. Large sections of channel still with very little vegetation at all.
Middle South Arm (S3, S4)	Significantly less vegetation than at any time in the past. Major instability in reaches with no vegetation (eg. S3).
Lower South Arm (S5)	Slight increase both above and below Buckra Bendinni Creek confluence.
Upper Taylors Arm (T1 - T2)	Significant local increases in river oak colonisation, however, not continuous - large sections of channel still with very little riparian vegetation.
Middle Taylors Arm (T4 - T8)	More vegetation than in 1964 and 1942
Lower Taylors Arm (T9 - T11)	Vegetation extent relatively unchanged (although community composition undoubtedly will have).
Upper Warrell Creek (W1)	Little change from the 1964 vegetation extent (1942 aerial photographs not available)
Lower Warrell Creek (W3)	Little change from the 1964 vegetation extent (1942 aerial photographs not available)
Middle Deep Creek (D2)	Little change from the 1964 vegetation extent (1942 aerial photographs not available)
Lower Deep Creek (D3)	As for middle Deep Ck. Except for the unstable section at Site D3, where vegetation is locally reduced.

5.10.3 Riparian Vegetation Changes and Channel Instability

It has been proposed by some landowners in the Nambucca catchment that there is a causal relationship between increased riparian vegetation (primarily river oaks) and channel instability. For this proposal to be accepted we must be able to demonstrate a *consistent* pattern of gross channel instability *following* riparian vegetation regrowth.

From the evidence presented this proposal can be emphatically rejected. There is no evidence that increased riparian vegetation has in general *caused* channel instability. The following examples demonstrate the point:

- Between 1964 and 1991, the few kilometres upstream of the bridge at Site M2 on Missabotti Creek probably experienced the greatest increase in the extent of river oaks, both in and adjacent to the channel, of anywhere in the catchment. Yet channel stability in this reach apparently improved over this same period. There has, however, been a new phase of instability since 1995 in this reach, following the upstream transmission of a new nickpoint (or series of nickpoints). In this case it was bed degradation associated with nickpoint migration that caused channel instability, not the riparian vegetation.

- The lower reaches of Missabotti Creek over the period 1964-1991 have experienced virtually continuous instability at the same time as there were increases in vegetation in some sections of river and fairly extensive clearance in others (plus significant gravel extraction). Instability occurred irrespective of whether there was vegetation in a reach.

- At two of the unstable sections of channel in the catchment, the floodplains around sites N3 and S3, channel instability has worsened at the time that the extent of vegetation decreased. However, it must be said that the initial distribution of vegetation (i.e. 1942 condition) was not extensive at either of these sites, and both have also been subject to extensive gravel extraction (M. Argent, pers. comm.).

- On South Arm, around its confluence with Buckra Bendinni Creek, it was apparent that there had been an increase in the extent of vegetation between 1964 and 1991, both above and below the confluence. Yet, South Arm below the Buckra Bendinni Creek

confluence was substantially destabilised by 1991, whereas this was not so above the confluence.

- On the middle reaches of Taylors Arm sites of active channel erosion do not exclusively correlate with reaches where there has been an increase in the extent of river oaks.

Further insights into the relationship between channel instability and river oaks can be gained by looking at their behaviour in other catchments. Some tributaries of the Hunter River (eg. Baerami Ck and Widden River) have had equivalent increases in the extent of river oaks since the 1950's as has the Nambucca, without any deleterious impact on channel stability. The difference with these cases being that the influx of river oaks was not accompanied by systemic bed degradation (Brooks et al., 1997). If river oaks are a cause of bed degradation, the same extent of degradation would be expected to have occurred on any other river showing an increase in the river oak population.

5.10.4 Hillslope Vegetation and Land Use Intensity

A further striking observation that can be made from the aerial photograph evidence is that of a quite profound increase in the extent of forest cover on many hillslopes throughout much of the catchment. Of the three time-slices surveyed from aerial photographs, it is apparent that the majority of this increase occurred after 1964 - very little change being observed between 1942 and 1964. A number of implications may be able to be drawn from this:

- With the decline of dairying, the intensity of farming in the valleys has declined since the 1960's - indicating that the underlying cause of post 1950's river-channel destabilisation is not solely related to increased farming intensity.

- The extent of channel degradation already visible in the 1942 aerial photographs highlights the extent of disturbances in the first half of the twentieth century, and probably the late nineteenth century as well, priming the channels for major disturbance once the appropriate flood triggers were applied by a significant change on flood regime in the 1950's.

5.10.5 Vegetation Changes Over the Past 50 Years - Conclusions

- In many sections of the Nambucca system there clearly has been an increase in the extent of riparian vegetation - primarily river oaks. Much of this increase has occurred at the same time as dramatic increases in channel instability. However, river oaks or other riparian species, have not *caused* the instability. As an opportunistic species they have occupied the bar alluvial surfaces created by channel erosion. In other words, the expansion in the extent of river oaks is largely a *response* to the channel instability - i.e. there has been a increase in habitat suitable for colonisation of such a species.

- River oaks, therefore, should be seen as a species with many of the appropriate characteristics to aid river rehabilitation, if managed properly.

- The causes of channel instability and bed degradation must be addressed, as outlined in Chapter 8.

- In channels subjected to major bed lowering associated with nickpoint retreat, bank erosion is an inevitable consequence. Because their root system is inevitably undermined, few riparian species will remain standing under these circumstances. When substantial bed degradation occurs, the channel will adjust to similar dimensions regardless of whether there is grassed or fully forested banks and floodplains.

- The main difference between the two extremes of a fully grassed and an extensively forested riparian zone, is largely the result of the recovery process after bed degradation has occurred. Under the forested conditions the channel becomes filled with LWD. Locally this may cause bank scour, which in turn may lead to increased sinuosity, but this is a necessary part of channel recovery following such instability. Overall a large volume of LWD aids bed stabilisation and aggradation, leading to at least partial rehabilitation of the fluvial system.

5.11 Riparian Vegetation Buffer Strips

Many of the benefits of riparian vegetation buffer strips were reviewed by Raine (1994). From a geomorphic perspective there are a number of benefits in having a buffer strip that extends beyond the immediate bank zone. This brief outline is a precursor to the management recommendations found in Chapter 8.

- In river reaches that currently exhibit active lateral migration, it is highly unlikely that any management strategy is going to immediately halt such erosion. Particularly in the early months and years of a revegetation program it is quite possible that considerable lateral erosion may continue. If only a narrow strip of vegetation is planted, even a minor amount of erosion can result in the loss of the entire the buffer zone. The wider the strip, the greater the chance of plants surviving to maturity. This of course assumes that bed degradation issues are tackled previously or simultaneously reducing the amount of channel instability.

- A vegetation strip wider than just the bank zone will offer a higher flow resistance during overbank flows. Higher floodplain flow resistance will further reduce in-channel velocities and the reduction of in-channel flow velocities is one of the primary long-term management objectives to control erosion.

- From a bank strength perspective, a combination of deep rooted species and species with dense surficial root mats is most desirable. This is best achieved in the long term by having greater species and structural diversity. The ideal condition is the kind of structural diversity found in riparian rainforest. Ecologically this can only be achieved with a larger buffer strip.

In some highly unstable channel sections in the middle reaches of some tributaries (eg. N3), it is possible that a narrow and densely vegetated riparian zone was established with the adjacent floodplain area containing only a grass covering. Over time the channel was substantially narrowed so that during an extreme flood the flow could adopt a preferred route down the distal margin of the floodplain, and hence cause floodplain stripping (*sensu*, Nanson, 1986). In extreme cases complete channel avulsion could occur. Such

a situation is most likely to arise when the riparian zone is fairly narrow, but dominated by seeding willows, and where there is no vegetation other than grass on the floodplain.

At sites such as this, in addition to the riparian buffer strip, a series of vegetated belts running perpendicular to the channel should be planted across the floodplain. These will have the effect of reducing flow velocities across the floodplain in extreme floods, and hence reducing the likelihood of floodplain stripping.

6. TERRACE AND FLOODPLAIN CHRONOLOGY

6.1 Introduction

This chapter presents the terrace and floodplain ages recorded in the Nambucca catchment. Dating these sediments gave an indication of episodes of late Quaternary fluvial activity and provided an opportunity to determine the extent of fluvial activity prior to settlement in the mid-nineteenth century.

An examination of radiocarbon ages in the neighbouring Bellinger catchment (Warner, 1972) indicated that floodplain ages would be primarily limited to Holocene ages, whilst terraces would pre-date these into the Pleistocene. To provide accurate dating of the different age structures there were two dating methods used. Radiocarbon dating was used for floodplain dating, as this technique was deemed more appropriate for Holocene sediments. Terrace samples were analysed using thermoluminescence dating, which was adjudged as providing improved accuracy for Late Pleistocene aged materials.

6.2 Dating Methods

6.2.1 Thermoluminescence Dating

Thermoluminescence (TL) is the thermally stimulated emission of light from a crystalline mineral following previous adsorption of energy from ionising radiation (Aitken, 1990). During sediment transport, and prior to burial, previously trapped electrons may be released as a result of exposure to sunlight. With sufficient exposure, the TL signal is reset to a minimum unbleachable level. Given the estimated dose rate, the TL output indicates the time since deposition and burial of the sediment occurred. The calculated date can give a reliable estimate of the age of deposition, although incomplete bleaching may result in overestimating the time since deposition.

Any residual, or unbleached, TL can often be detected by a 'plateau test' (Smith et al., 1982) of the curve plotting temperature against the ratio of natural TL output to that induced in a sample that has been bleached of residual TL and then given a laboratory radiation dose approximately equivalent to the radiation received by the sediment since

deposition. A clearly defined plateau developed beyond 300-325°C, where electrons are very readily bleached by exposure to UV-depleted sunlight, provides confidence in the bleaching of the sediment (Price, 1994; Page et al., 1996). A distinct foreshortening of the temperature/TL plateau is indicative of significant residual TL (Smith et al., 1982).

It has been shown over the last decade or so (eg. Olley et al., 1998) that such difficulties encountered in TL dating can often be removed by the application of the optically stimulated luminescence (OSL) technique. However, research for this study was undertaken when the School of Geosciences at the University of Wollongong had only TL dating facilities. Nonetheless, ongoing comparative studies at the University involving TL and OSL applied to matched pairs of sedimentary samples indicate that, when applied carefully, TL analysis does yield reliable chronologies for alluvial sequences. Sanderson et al. (2001) have also reported TL and OSL datasets that are compatible with each other. Nevertheless, the TL results presented here do need to be viewed with a degree of caution, as TL and OSL comparisons have not been undertaken in this specific environment.

TL samples were analysed by means of the combined additive and regenerative methods using the 90-125 micrometre quartz grain size fraction, which was separated from the bulk samples provided and suitably compared. This technique ensures that there has been no change in TL sensitivity due to the particular laboratory procedure followed. Corrections have not been made for surface residual TL there being no modern analogue sample available for this purpose. In this situation it is normal to assume that the TL level at the time of deposition is that reached following a minimum 24 hour sample exposure beneath a laboratory ultraviolet lamp (Philips MLU 300W). This assumption may, in certain circumstances, tend to produce an age over-estimation. The level of this is dependant on the effectiveness the solar resetting of any previously acquired TL prior to the final deposition phase of the sample under investigation. In the majority of cases in this study the TL characteristics displayed by these samples suggest that all but two samples, W2729 and W2730, had effectively reset.

Samples W2729 and W2730 from Site 2 Warrell Creek exhibited stepped temperature plateau comparisons, which suggests ineffective resetting of previously acquired TL prior

to deposition. These samples were therefore analysed at 300-325°C which represents the more easily reset electron trap level. Although there is a short plateau at this temperature the ages derived for these two samples may still represent an over-estimate. Samples taken from Site 3 on Warrell Creek exhibited a lengthy temperature plateau suggestive of effective solar resetting. These, and all other samples, were analysed at the more stable 375°C electron trap level.

All samples taken from Warrell Creek exhibited a quite different second glow curve characteristic compared to those samples collected from other study sites. It would appear therefore that the quartz contained within the Warrell Creek samples has different provenance to that contained in other samples. This sediment therefore appears to have a different geological origin.

6.2.2 *Radiocarbon Dating*

Radiocarbon dating is the dominant technique for dating organic samples that are less than 40 000 years old - wood (and charcoal), bone, peat, seeds, cloth, etc. The weakly radioactive isotope ^{14}C, with a half-life of 5730 years (Aitken, 1990), is present in the atmosphere and in all living plants and animals and in the dissolved carbonates of the ocean. When plant cellulose, bone or shell are formed, the carbon atoms are fixed and so are cut off from the reservoir of ^{14}C; hence radioactive decay is no longer balanced by neutron induced production and the specific activity should decrease according to the ^{14}C half-life (Aitken, 1990).

Regardless of the experimental quality of a laboratory the ultimate limitation in age range is around 40 000 years—because the sample-plus-background count-rate then becomes indistinguishable from the background count-rate. However, by employing thermal diffusion columns to obtain isotopic enrichment before measurement several laboratories have achieved five-fold enrichment of 14 relative to 12 thereby pushing back the limiting age to around 70 000 years. For this, and indeed in any case, the absence of contamination is crucial, particularly contamination by modern carbon. The presence of 1% modern carbon in a 34 000-year-old sample will cause the age to be underestimated by 4000 years; for an infinitely old sample the apparent age will be 38,000 years (Aitken, 1990).

During the 1980's several laboratories initiated the use of accelerator mass spectrometry (AMS) using a tandem electrostatic generator for acceleration of the ions. Higher voltages than those used in ordinary mass spectrometry are needed in order that various nuclear physics techniques can be used for particle detection and discrimination against unwanted ions. The basic advantage of AMS is that it is essentially an 'atom counting' technique; this is highly advantageous compared with beta counting because only 1% of the ^{14}C atoms emit a beta particle in about 80 years. Using only a few milligrams, depending on the age of the sample, a statistical precision of 0.5% can be obtained in a few hours with AMS (Aitken, 1990).

6.3 Results

Terrace and floodplain ages are presented in this section. TL samples have their ages presented in thousands of years (ka), whilst radiocarbon ages are presented in years before present (i.e. 1950) (yrBP).

6.3.1 Results of Thermoluminescence Sampling

To reveal the age of the older terrace sequences in the Nambucca catchment, nineteen (19) samples were TL dated. The younger material found in the floodplains are radiocarbon dated as this method is probably more accurate than TL for dating material likely to be of Holocene-age. Tabulated TL data is presented in Table 6.1 and the stratigraphies of selected sample sites are shown in Figures 6.1 to 6.8. Full details of the TL analysis for each sample are presented in Appendix 10.

Table 6.1: Thermoluminescence ages of selected terraces in the Nambucca catchment

Site	Material Type	Stratigraphic Position	Dating Method	Identifier	Age 000's years (ka)
T4	Yellow/Brown Silty Clay	8.5 m above base of channel 30 m from left bank	TL	W2352	50.9 ±11.2
T4	Yellow/Brown Silty Clay	Terrace 50 from channel; 3m below ground surface. Left bank	TL	W2718	54.6± 5.4
T4	Grey Sandy Clay	Terrace 50 from channel; 9m below ground surface. Left bank.	TL	W2719	52.9 ± 4.5
T9	Brown Silty Clay	Terrace 80 m from channel; 4.5 m below ground surface. Right bank.	TL	W2720	15.4± 1.3
T9	Brown Silty Clay	Terrace 80 m from channel; 8.3m below ground surface. Right bank.	TL	W2721	16.6± 1.3
N3	Brown Silty Clay	Terrace 200 m from channel; 6m below ground surface. Left bank.	TL	W2724	19.5 ± 3.6
N3	Brown Silty Clay	Terrace 200 m from channel; 9m below ground surface. Left bank.	TL	W2725	16.4 ± 1.2
N6	Brown Sandy Clay	Terrace 20 m from channel; 3m below ground surface. Right bank.	TL	W2722	10.1 ± 2.1
N6	Brown Sandy Clay	Terrace 20 m from channel; 4.5 m below surface. Right bank.	TL	W2351	16.2 ± 2.1
N6	Brown Sandy Clay	Terrace 20 m from channel; 9m below ground surface. Right bank.	TL	W2723	20.9± 4.4
S5	Brown Sandy Clay	Right terrace 90 m from channel; 4m below ground surface.	TL	W2726	19.3 ± 1.4
D3	Brown Silty Clay	Left Terrace 100 m from channel; 4.5 m below ground surface	TL	W2727	36.1 ± 3.2
D3	Brown Silty Clay	1m above base of channel Exposed left hand bank	TL	W2349	53.2 ± 6.1
D3	Red/Brown Silty Clay	2m above base of channel Exposed right hand bank	TL	W2350	25.5 ± 2.1
D3	Red/Brown Silty Clay	Right terrace 30 m from channel; 4.5 m below ground surface.	TL	W2728	31.0 ± 3.0
W2	Brown Silty Clay	Terrace 70 m from channel; 1.5 m below ground surface. Right bank.	TL	W2729	11.6± 0.9
W2	Brown Silty Clay	Terrace 70 m from channel; 6m below ground surface. Right bank.	TL	W2730	12.6 ± 1.1
W3	Yellow/Red Silty Clay	Terrace 210 m from channel; 1.5 m below ground surface. Left bank.	TL	W2731	13.4 ± 1.1
W3	Brown Silty Clay	Terrace 210 m from channel; 6m below ground surface. Left bank.	TL	W2732	78.1 ± 6.5

Taylors Arm Site 4: The terrace samples were taken from an exposure some 30 m from the current channel and at heights between 1.5 and 8.5 m above the channel (Figure 6.1). TL dates of 50.9±11.2 ka (W2352), 52.9±4.5 ka (W2719) and 54.6±5.4 ka (W2718) were obtained from this terrace, which would be classified as a T_{3-4}, residual terrace under the Warner (1972) classification. All three dates are within the uncertainty limits suggesting the terrace is in the order of 53 ka in age.

Taylors Arm Site 9: The terrace TL samples were collected from drill hole samples taken 80 m from the existing channel. The samples represent levels 3.5 m and 7.3m above the height of the current channel (Figure 6.2). The two terrace samples were dated at 16.6±1.3 ka (W2721) and 15.4±1.3 ka (W2720), suggesting the terrace is of about 16 ka in age.

North Arm Site 3: The terrace samples were located 180 m away from the existing channel and at 5 and 7m below the ground surface in a massive unit of mottled brown clays (Figure 6.3). The samples yielded dates of 19.5±3.6 ka (W2724) and 16.4±1.2 ka (W2725). These ages correspond to T_2 main terraces under the Warner (1972) classification. The two dates indicate a reversal in the expected chronology, however given the error bands associated with the samples it suggests that the terrace is about 16-20 ka.

North Arm Site 6: A young terrace exposure was located on the downstream end of North Arm. The grey sandy clay in the terrace was TL dated at 20.9±4.4 ka (W2723), 16.2±2.1 ka (W2351) and 10.1±2.1 ka (W2722) (Figure 6.4). Under the Warner (1972) classification this unit would be a very young T_2, main terrace and appears to reflect progressive aggradation from the Last Glacial Maximum (LGM) to the early Holocene.

South Arm Site 5: A section of remnant terrace was drilled with a sample taken 75 m away from the channel at a height of 4m above the channel bed (Figure 6.5). This TL sample yielded a date of 19.3±1.4 ka (W2726), which indicates a T_2 (main terrace) under the Warner (1972) classification. The age of this terrace appears to be similar to the terraces at sites T9, N3 and N6.

Deep Creek Site 3: TL samples were taken on both the right and left bank exposed terraces. The right bank terrace (Figure 6.6) was dated as a T_2, main terrace (Warner, 1972) with ages of 25.5±2.1 ka (W2350) and 31.0±3.0 ka (W2728). The left terrace was dated at 53.2±6.1 ka (W2349) and 36.1±3.2 ka (W2727), or a T_{3-4}, residual terrace. Both samples were taken from massive units of mottled red/yellow/grey silty clays. However, the left terrace contained a large gravel unit at the base of the unit. There was no gravel found at the base of the right terrace.

Warrell Creek Site 2: Two TL samples were collected from a drill hole into the only visible terrace at this location. The samples were located 70 m from the channel at heights of 3m and 7.5 m above the existing channel (Figure 6.7) and yielded ages of 12.6±1.1 ka (W2730) and 11.6±0.9 ka (W2729), respectively.

Warrell Creek Site 3: A drill hole was used to collect TL samples from the high terrace, 210 m from the channel and 4.5 m and 9m above the channel bed (Figure 6.8). The dates obtained were 78.1±6.5 ka (W2732) and 13.1±1.1 ka (W2731), respectively.

TAYLORS ARM SITE 4

Catchment Area 15,845ha

Surface Grain Size: 30±16mm
% Quartz: 50.82%
Subsurface D_{50}: 10.70 mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

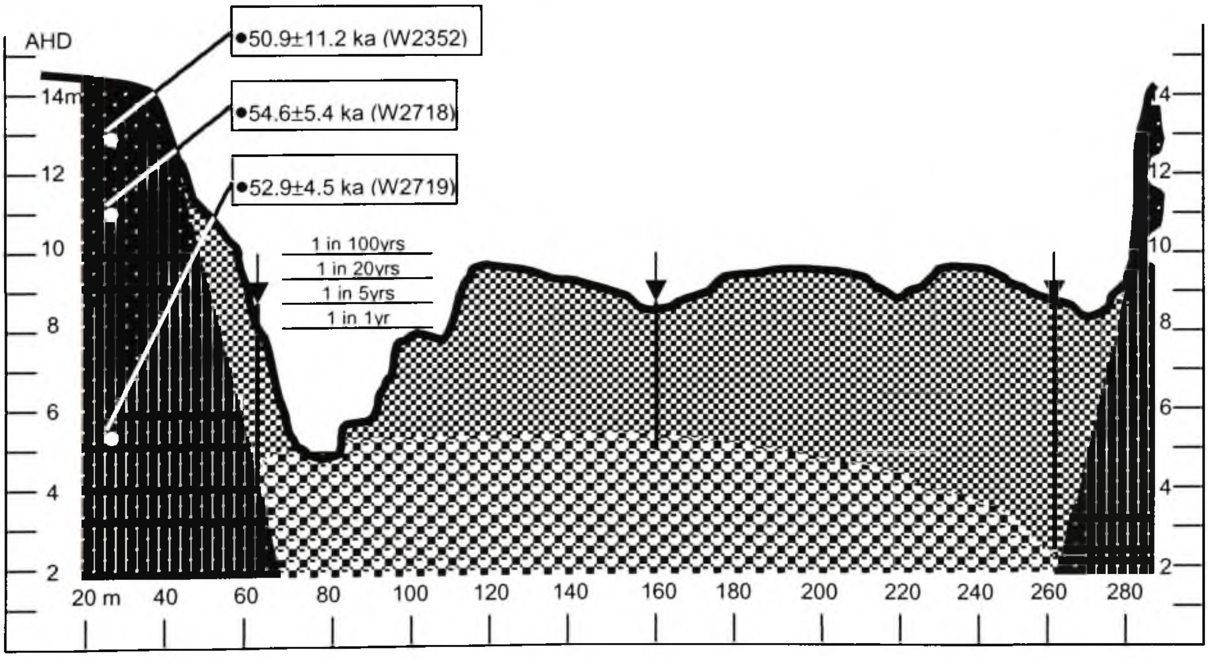


Figure 6.1: Stratigraphy, chronology and site photo – Taylors Arm Site 4

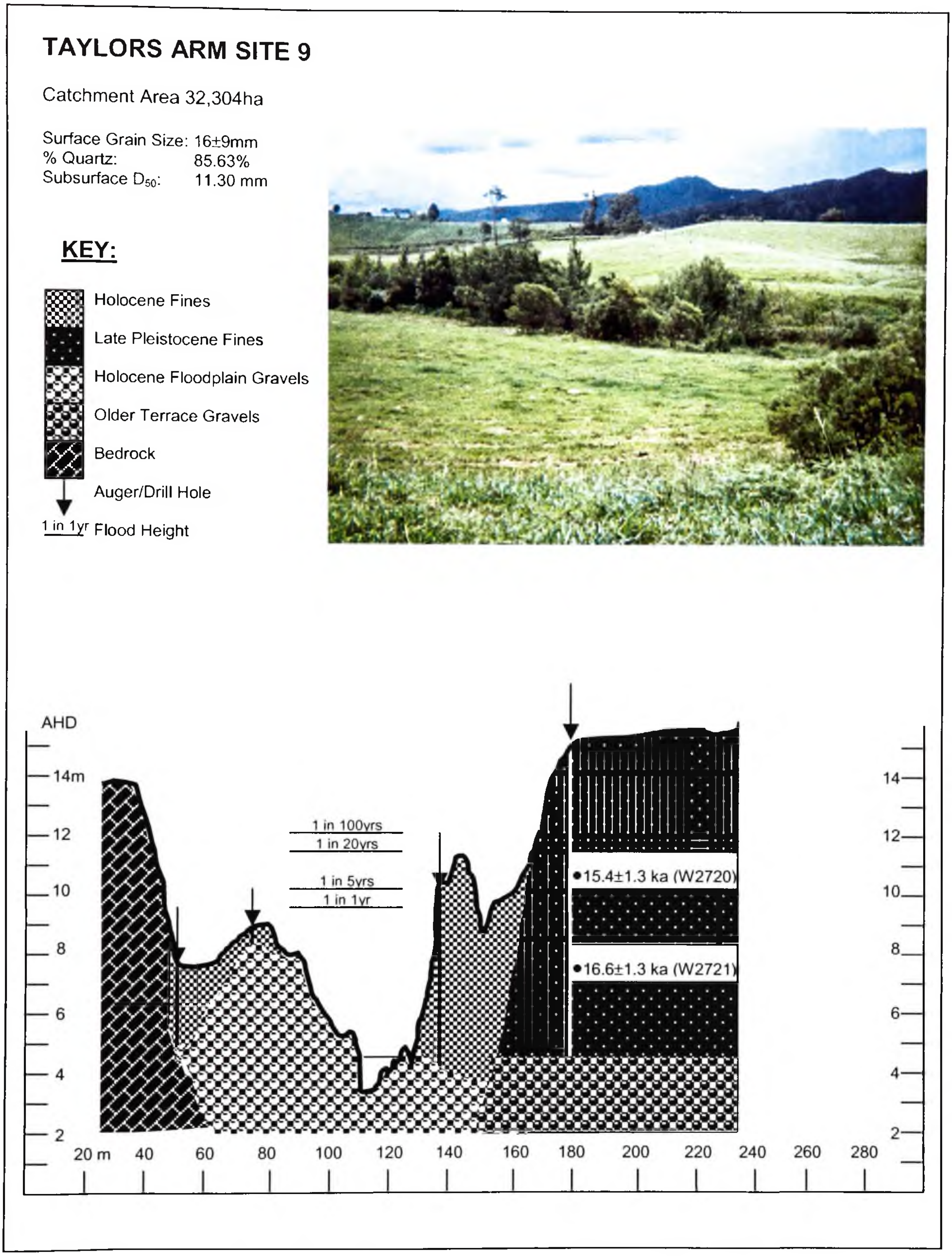


Figure 6.2: Stratigraphy, chronology and site photo – Taylors Arm Site 9

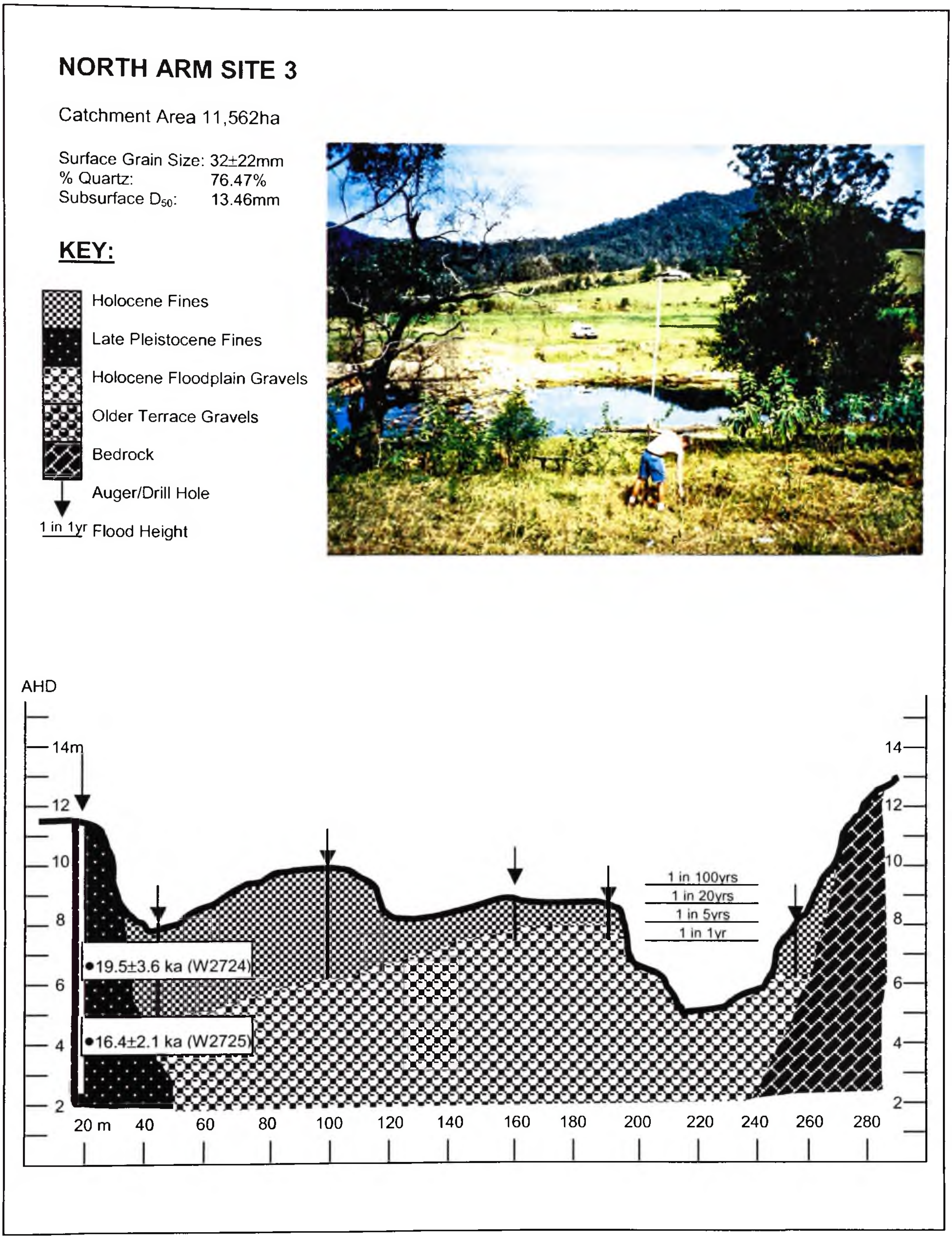


Figure 6.3: Stratigraphy, chronology and site photo – North Arm Site 3

NORTH ARM SITE 6

Catchment Area 24,067ha

Surface Grain Size: 22±11mm
% Quartz: 95.08%
Subsurface D_{50}: 8.31mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

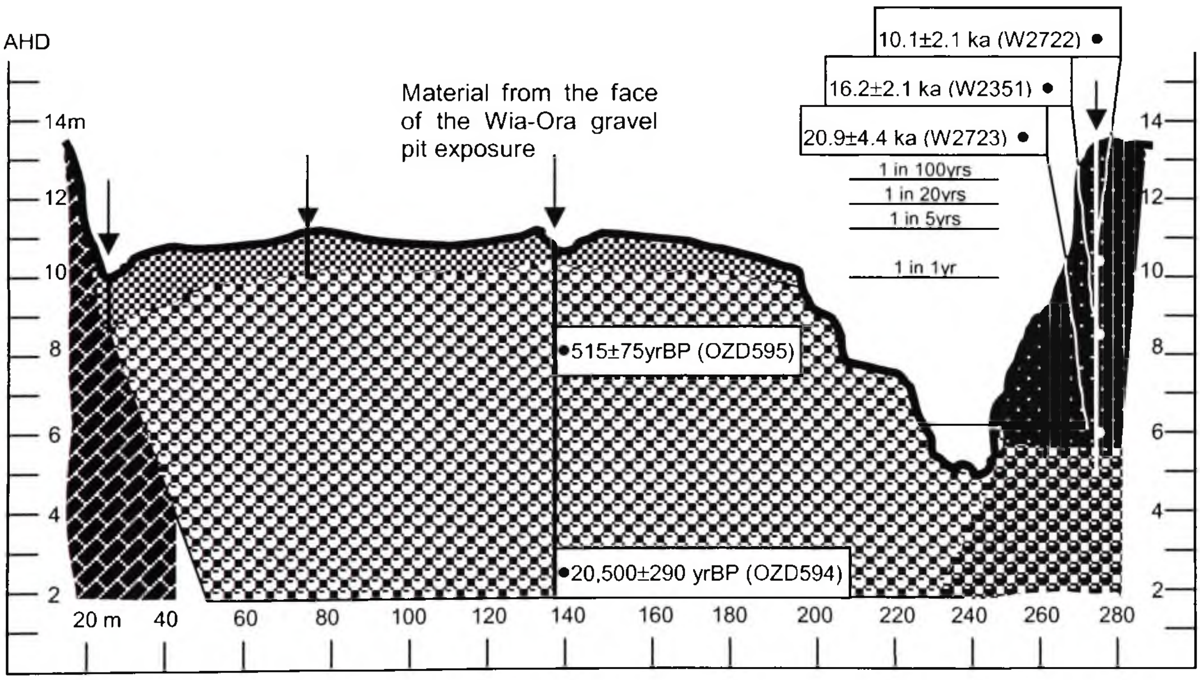


Figure 6.4: Stratigraphy, chronology and site photo – North Arm Site 6

SOUTH ARM SITE 5

Catchment Area 17,162ha

Surface Grain Size: 17±8mm
% Quartz: 97.50%
Subsurface D_{50}: 9.35 mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

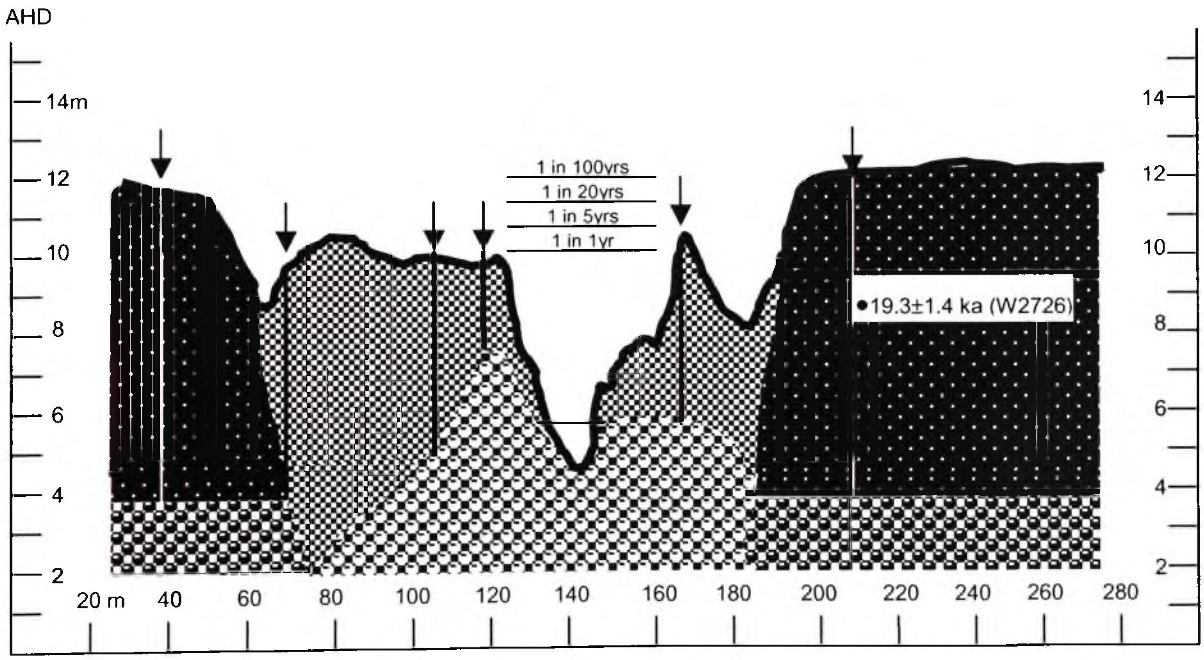


Figure 6.5: Stratigraphy, chronology and site photo – South Arm Site 5

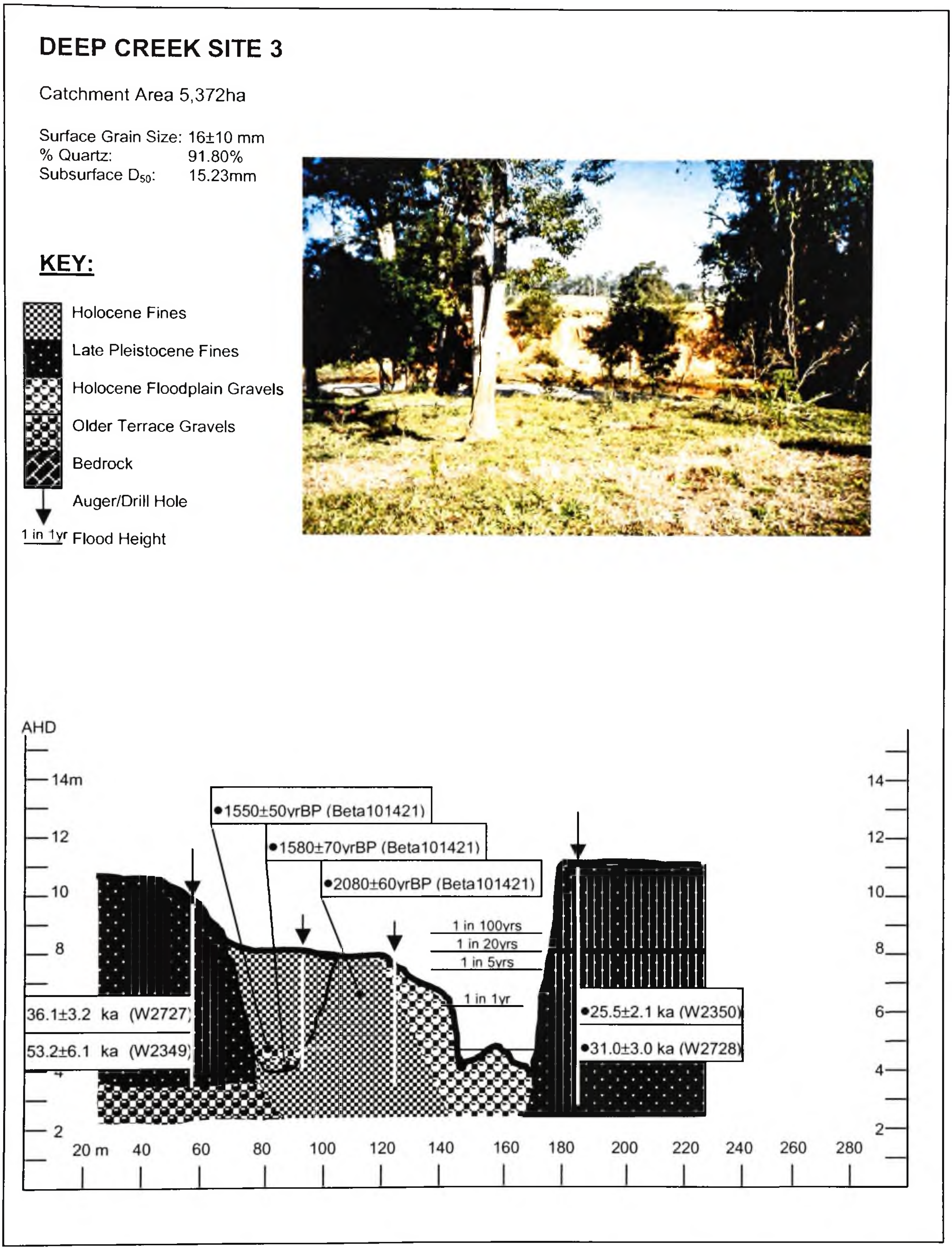


Figure 6.6: Stratigraphy, chronology and site photo – Deep Creek Site 3

WARRELL CREEK SITE 2

Catchment Area 7,268ha

Surface Grain Size: 10±6mm
Subsurface D_{50}: 5.07mm

KEY:

Holocene Fines
Late Pleistocene Fines
Holocene Floodplain Gravels
Older Terrace Gravels
Bedrock
Auger/Drill Hole
1 in 1yr Flood Height

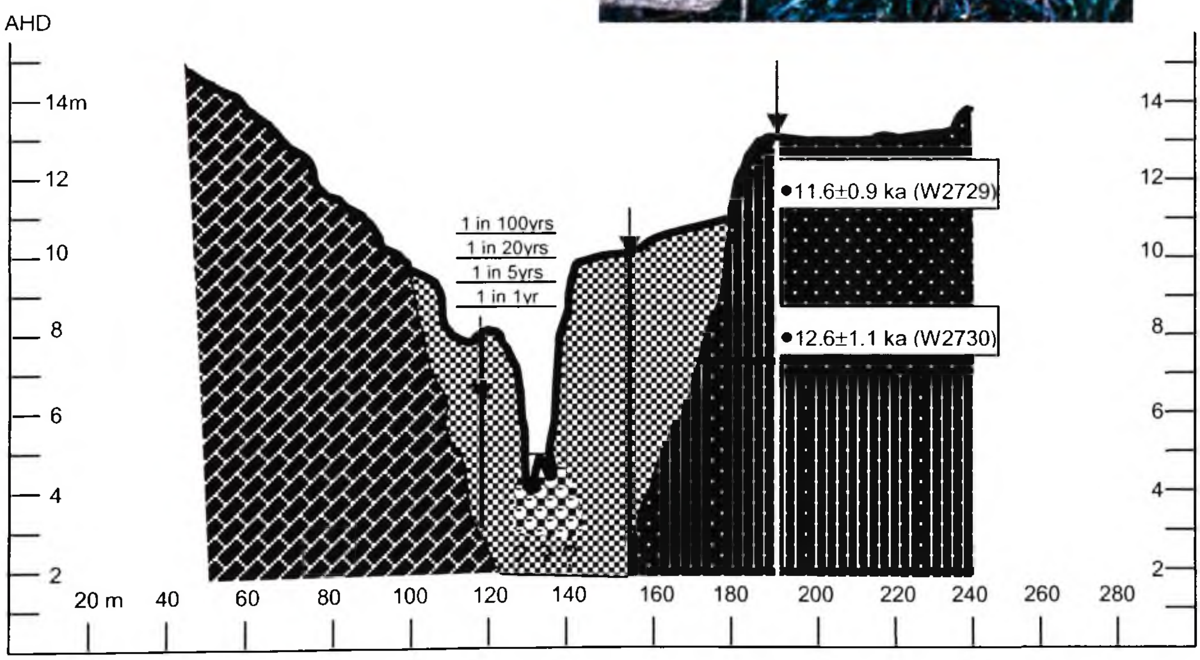


Figure 6.7: Stratigraphy, chronology and site photo – Warrell Creek Site 2

WARRELL CREEK SITE 3

Catchment Area 19,000 ha

Surface Grain Size: 14±10 mm
Subsurface D_{50}: 6.26mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

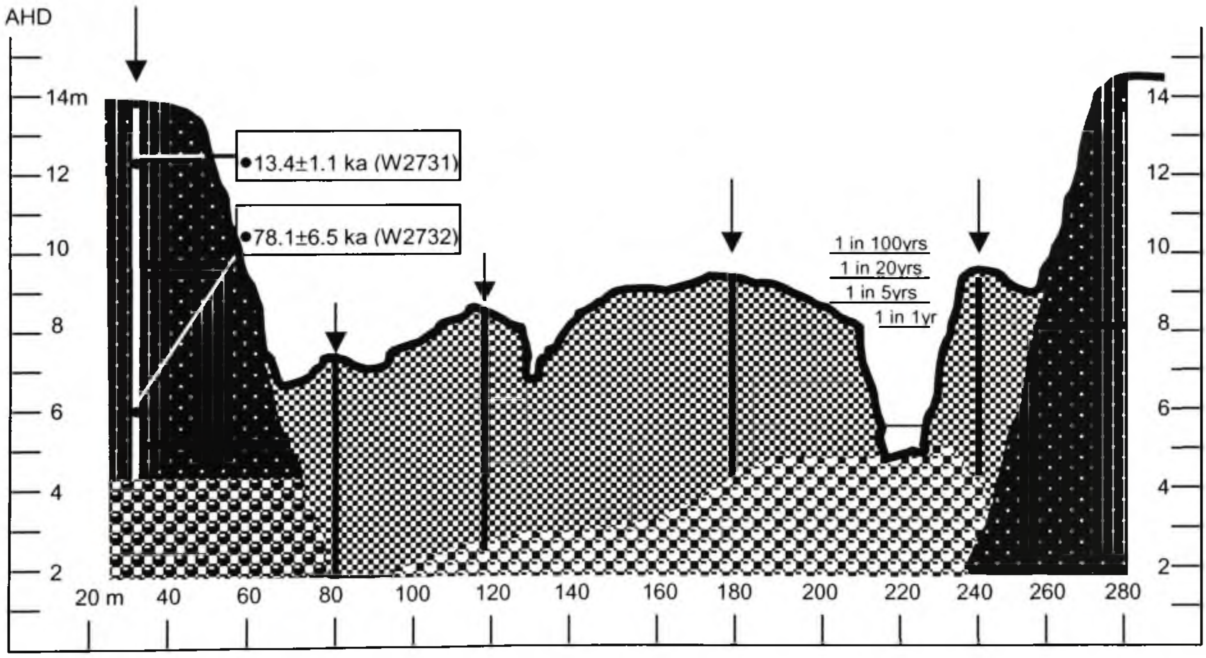


Figure 6.8: Stratigraphy, chronology and site photo – Warrell Creek Site 3

6.3.2 Summary

The nineteen TL dates acquired on the Nambucca terraces all correspond to periods of significantly enhanced fluvial activity during the late Quaternary from the Colleambally, Kerarbury, Gum Creek and Yanco phases dated on the Riverine Plain and Cranebrook terraces in southeastern Australia (Nanson et al., 2003).

The oldest remnant terrace of 78.1±6.5 ka (W2732) was located on the lower end of Warrell Creek (W3), and represents a period of fine-gravel vertical accretion probably in late OIS 5 (Colleambally). Terrace dates from T4 [50.9±11.2 ka (W2352), 52.9±4.5 ka (W2719) and 54.6±5.4 ka (W2718)] and the left terrace on D3 [53.2±6.1 ka (W2349) and 36.1±3.2 ka (W2727)] correspond to early OIS 3 (Kerarbury – Warner's residual $T_{3\text{-}4}$ terraces), whilst the left terrace at D3 [25.5±2.1 ka (W2350) and 31.0±3.0 ka (W2728)] corresponds to late OIS 3 (Gum Creek).

The remainder of the terraces dated in the Nambucca catchment correspond to late OIS 2 (Yanco) and indicate enhanced activity around 20-10 ka. These correspond to Warner's (1972) T_2 terraces and are supported by dates from the middle and lower units of terraces at sites T9 [16.6±1.3 ka (W2721) and 15.4±1.3 ka (W2720)], N3 [19.5±3.6 ka (W2724) and 16.4±1.2 ka (W2725)], N6 [19.5±3.6 ka (W2724) and 16.4±1.2 ka (W2725)], and S5 [19.3±1.4 ka (W2726)]. Warrell Creek in the south of the catchment and the lower end of North Arm indicate uppermost terrace units dating 13-11 ka [W2 at 12.6±1.1 ka (W2730) and 11.6±0.9 ka (W2729), and N6 at 10.1±2.1 ka (W2722)]. A more detailed description and analysis is given in Chapter 7.

6.3.3 Results of Radiocarbon Sampling

To examine recent channel and floodplain instability in the context of longer-term changes, fifteen radiocarbon samples were selected from floodplains at ten sites. Material collected was from charcoal layers in the floodplain stratigraphy, leaf materials in the grey clay-layer at the base of the floodplain deposits and, from a buried log protruding from an eroded bank. The tabulated radiocarbon results are presented in Table 6.2 and their stratigraphic details shown in Figures 6.9 to 6.16. For this study both conventional enrichment ^{14}C and AMS techniques were used. Ten (10) initial samples were analysed

by Beta Analytic Inc. Using conventional enrichment ^{14}C (Beta-101412 to Beta-101421) and a further five (5) underwent AMS dating at the AINSE laboratories (OZD594 to OZD598).

Table 6.2: Radiocarbon ages of floodplain material at selected sites in the Nambucca catchment

Site	Material Type	Stratigraphic Position	Dating Method	Identifier	Age (yrBP)
T5	Wood	Amongst grey clay at the base of the present stream bank.	C14	Beta101416	1,960 ±100
T5	Charcoal	4m above water level, 2m below the floodplain surface.	C14	Beta 101417	1,020 ± 60
T6	Wood	4m below surface (auger hole), 35 m from the left bank.	C14	Beta 101414	130 ± 60
N4	Leaves	Base of bank in fill sequence	C14	Beta 101415	440 ± 60
N6	Wood	3m below floodplain surface, 90 m from the left bank.	C14	OZD595	515 ± 25
N6	Cedar Log	From gravel pit; 9m below ground surface and 3m beneath watertable90 m from the left bank.	C14	OZD594	20,500 ±290
N7	Wood	3m below floodplain surface, 50 m from the left bank.	C14	OZD596	85 ± 60
M4	Leaves	Amongst grey clay at base of the present left bank.	C14	Beta 101413	2,660 ± 50
M4	Wood	3m above water level, 2m below surface and 80 m from the left bank.	C14	Beta 101412	2,330 ± 50
S3	Charcoal	2m above water level, 0.8m below surface and 5 m from the right bank.	C14	Beta 101418	690 ± 60
S4	Charcoal	Left bank exposure, 1m above water level.	C14	OZD598	285 ± 85
B2	Charcoal	2.5 m above water level on the left bank.	C14	OZD597	470 ± 80
D3	Charcoal	Remnant floodplain, 50 m from the left bank.	C14	Beta 101421	2,080 ± 60
D3	Charcoal	Channel fill material, 50 m from the left bank.	C14	Beta 101420	1,550 ± 50
D3	Leaves & Twigs	Amongst grey clay at base of fill sequence, 50 m from bank.	C14	Beta 101419	1,580 ± 70

Taylors Arm Site 5: The basal unit contained grey clay with organic matter dating at 1960±100 yrBP (Beta - 101416). The organics were interbedded in gravels (Figure 6.9), suggestive of a laterally active channel. Charcoal in the upper sandy loam at a depth of ~2.5 m was found to be 1020±60 yrBP (Beta-101417) and this, in combination with the fine-grained stratigraphy, is evidence for substantial overbank deposition. Floodplain accretion at this site was relatively rapid (>5 m in ~1000 years) following deposition of the gravels and the grey clay, but then slowed as the floodplain continued to progressively build by way of overbank deposition to existing levels.

Taylors Arm Site 6: A palaeochannel 45 m from the present channel, and clearly visible on 1942 aerial photographs, contained a wood sample which dated at 130±60 yrBP (Beta-101414) (Figure 6.10). Since abandonment, the palaeochannel has infilled with a silty sandy loam. This site provides evidence of a floodplain formed of overbank fines, containing a small channel, followed by later channel avulsion and incision of the present channel in these fines, probably near the time of European settlement.

North Arm Site 4: Leaf litter in the grey clay at the base of a clearly defined palaeochannel is adjacent to older orange stained iron and manganese coated gravels. This leaf material dated at 440±60 yrBP (Beta-101415) (Figure 6.11). Above the clays the palaeochannel consisted of about 6m of sandy loam rising to the present floodplain surface. This site provides evidence of abandonment of a palaeochannel much smaller than the present channel, about 450 years BP.

North Arm Site 6: Samples were collected here from a floodplain gravel pit located about 60 m from the present channel (Figure 6.4). A charcoal layer 3m below the surface and 100 m from the channel was dated at 515±75 yrBP (OZD 595). A cedar log was retrieved by excavator at a depth of 10 m below the surface (4m below the existing water table) and this was dated at 20,500±300 yrBP (OZD 594).

North Arm Site 7: A piece of wood was located here in silty loams 2m below the floodplain surface, 45 m from the existing channel and was dated at 85±60 yrBP (OZD 596). There was a further 4.5 m of clay loam beneath the sample before the water table and gravel profile is reached (Figure 6.12). This date represents modern material and

supports anecdotal evidence of floodplain accretion at this location in the past 50 years. It is noticeable that the floodplain is relatively low compared to other sites in the catchment, and anecdotal evidence suggests that this is one of the few floodplain locations still overtopped approximately once a year.

Missabotti Creek Site 4: Wood from a grey clay basal unit inset within orange stained quartz gravels dated at 2660±60 yrBP (Beta-101413) (Figure 6.13). This unit underlies an extensive 1.8m thick orange gravel unit that contains iron and manganese coated gravels. Above this gravel unit is up to 3m of sandy loam which dated at 2330±50 yrBP (Beta-101412) a little over a metre below the present floodplain surface, suggesting that the intervening ~5 m of fine overbank sediment was laid down in about 300 years. As with Site 5 on Taylors Arm (Figure 6.9), there is evidence here of rapid vertical accretion following deposition of the gravels, and then a period of much more gradual accretion as a stable floodplain has continued to slowly accrete overbank fines. The site as a whole is evidence of extensive channel migration and associated overbank deposition at about 2700 to 2300 years BP.

South Arm Site 3 (just upstream from S3): The upper level of remnant high floodplain dated at 690±60 yrBP at a depth of 0.6m below the floodplain surface (Figures 6.14). The sample was taken 1.5 m above the channel floor and the charcoal material dated was over a basal gravel unit consisting of imbricated phyllite/schistose sandstone clasts and finer overbank sediments. The site is located amid low benches and eroded floodplain units in what today is clearly an unstable reach where erodible gravel is very high in the stratigraphic profile. This ~700 year old sample suggests that, prior to land clearance, this vulnerable and rapidly reworking site may have been considerably more stable.

South Arm Site 4: A charcoal layer was located on the exposed left bank of the channel. The layer was found 1.5 m above the bed of the channel and 1m above the gravel layer and was overlain by 1m of sediment (Figure 6.15). The charcoal was dated at 285±85 yrBP (OZD 598).

Buckra Bendinni Creek Site 2: A layer of charcoal dating at 470±80 yrBP (OZD 597) was collected from the exposed left bank, 2.5 m above the existing channel bed (Figure

6.16), and immediately above a gravel lens. Above the gravel lense is a further 1m of silt overburden to the floodplain surface.

Deep Creek Site 3: A section dated from charcoal, in the upper part of the unit, yielded an age of 2080±60 yrBP (Beta-101421). The base, and fill material, of a palaeochannel buried within the floodplain bordering the left terrace was dated from charcoal and leaves and twigs at 1580±70 yrBP (Beta-101419) and 1550±50 yrBP (Beta-101420) respectively (Figure 6.6). Sometime later the channel avulsed to the opposite side of the narrow valley floor where it is currently eroding the right hand terrace. This site provides evidence of floodplain and channel stability prior to about 2000-1500 years BP and channel avulsion and infilling after that time.

TAYLORS ARM SITE 5

Catchment Area 18,405ha

Surface Grain Size: 17±14mm
% Quartz 77.05%
Subsurface D_{50}: 6.02mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

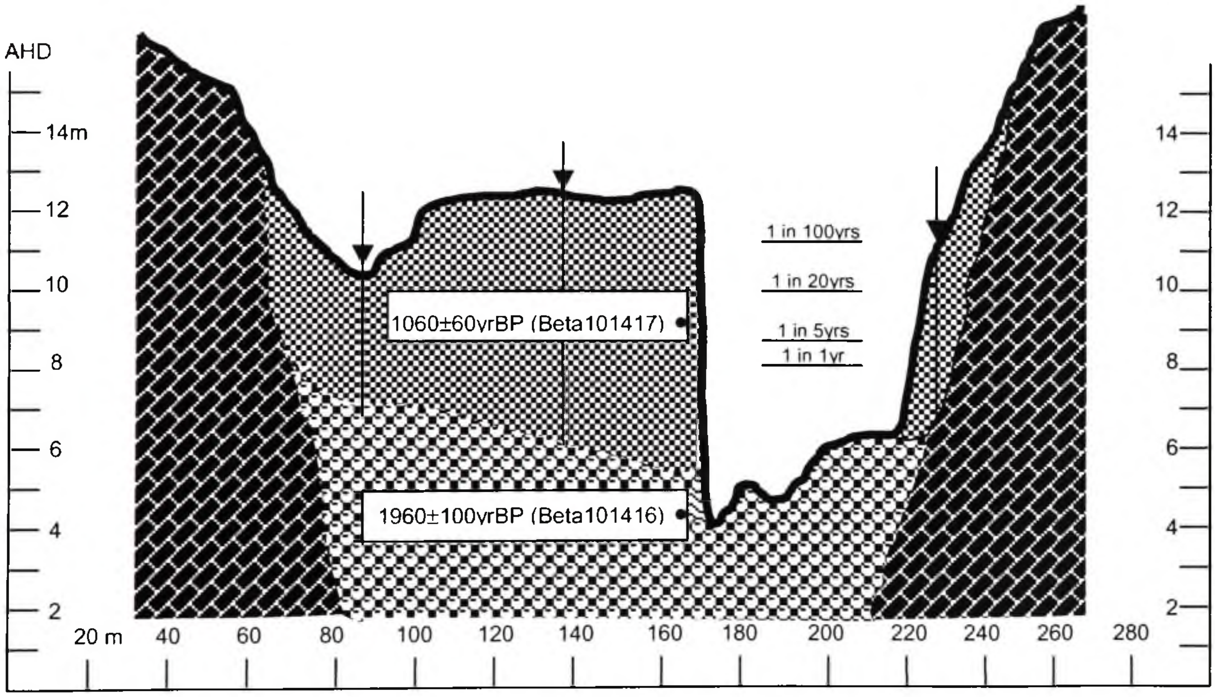


Figure 6.9: Stratigraphy, chronology and site photo – Taylors Arm Site 5

TAYLORS ARM SITE 6

Catchment Area 19,550 ha

Surface Grain Size: 39±16mm
% Quartz 81.08%
Subsurface D_{50}: 10.49mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

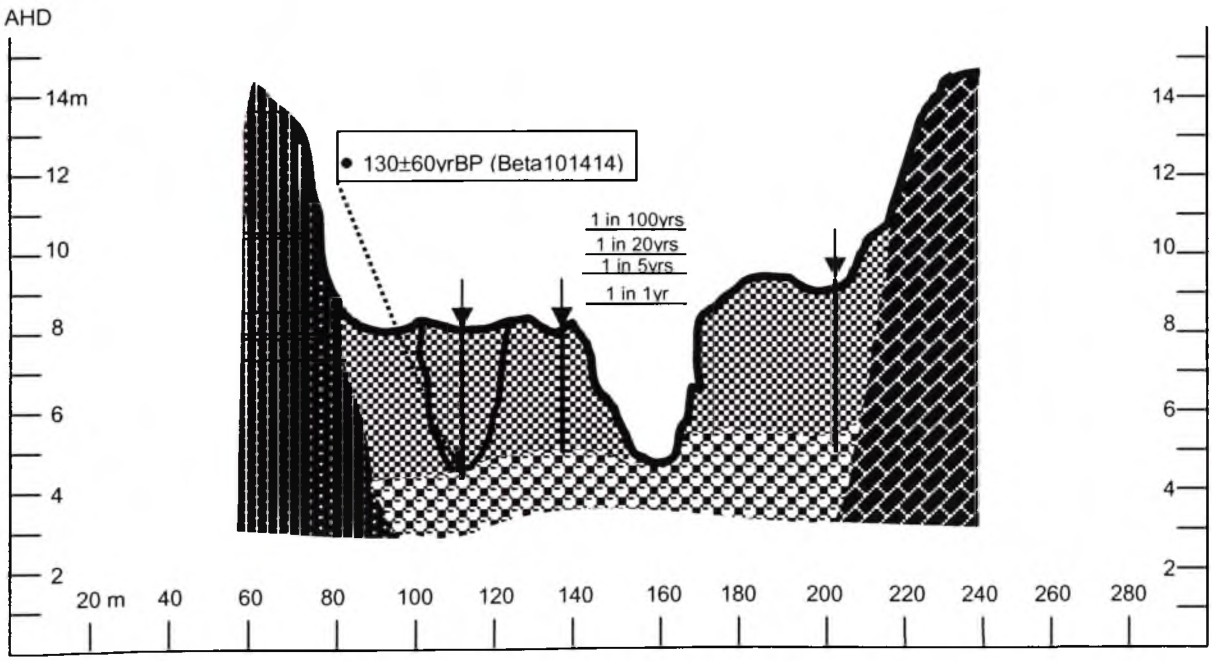


Figure 6.10: Stratigraphy, chronology and site photo – Taylors Arm Site 6

NORTH ARM SITE 4

Catchment Area 13,367ha

Surface Grain Size: 29±18mm
% Quartz: 91.80%
Subsurface D_{50}: 9.85 mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

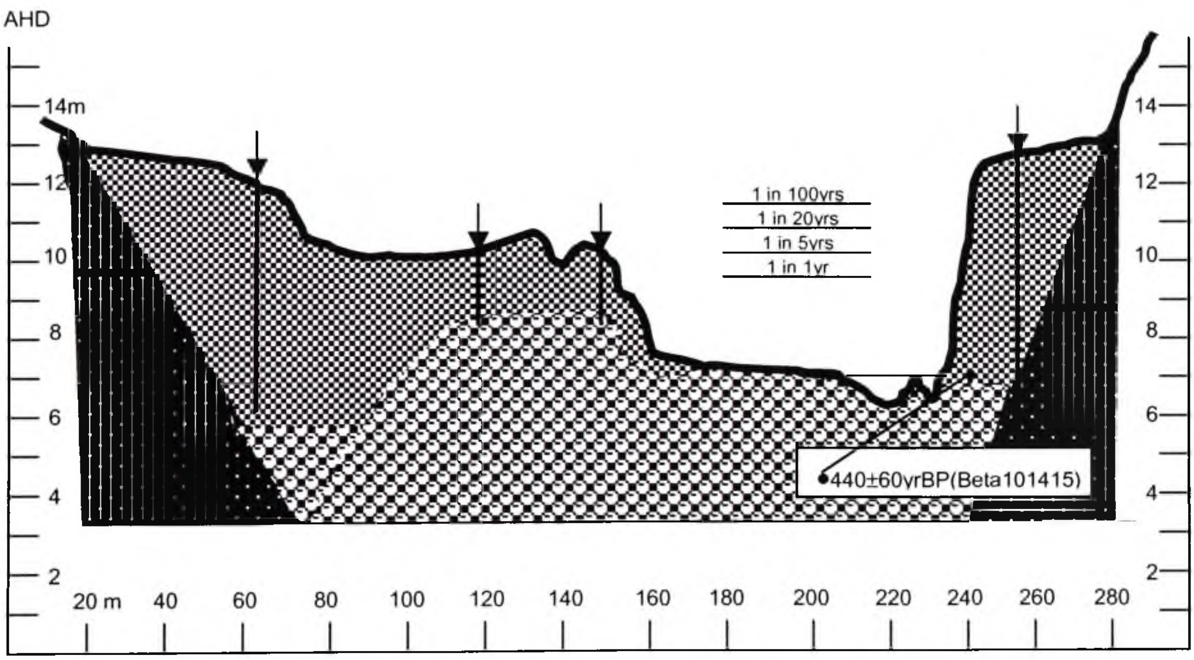


Figure 6.11: Stratigraphy, chronology and site photo – North Arm Site 4

NORTH ARM SITE 7

Catchment Area 32,304ha
Surface Grain Size: 19±10 mm
% Quartz: 98.38%
Subsurface D_{50}: 8.18mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

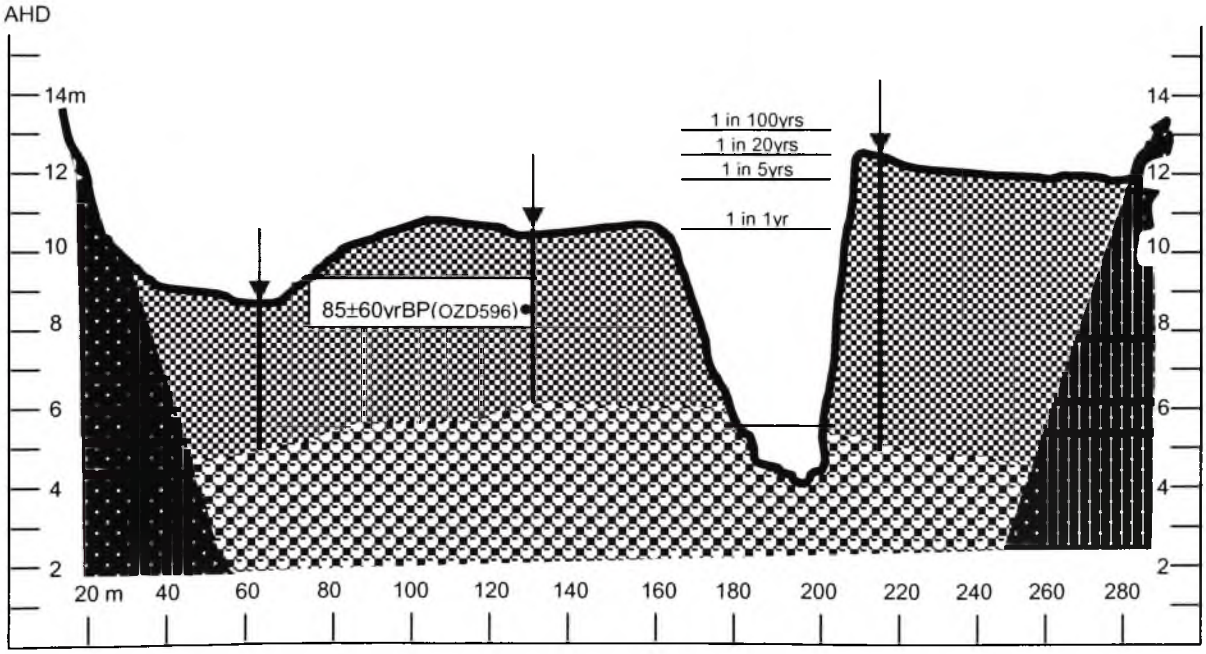


Figure 6.12: Stratigraphy, chronology and site photo – North Arm Site 7

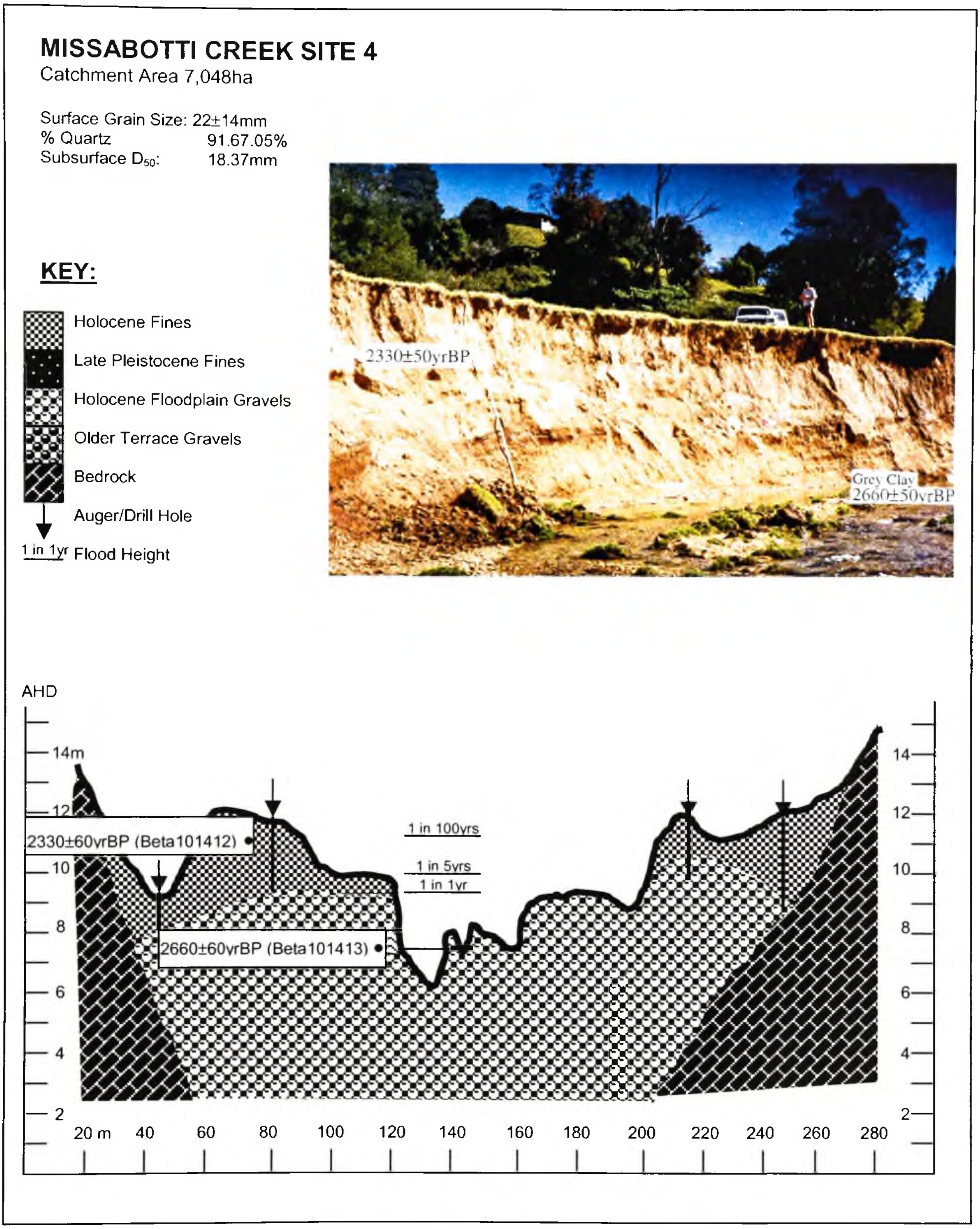


Figure 6.13: Stratigraphy, chronology and site photo – Missabotti Ck Site 4

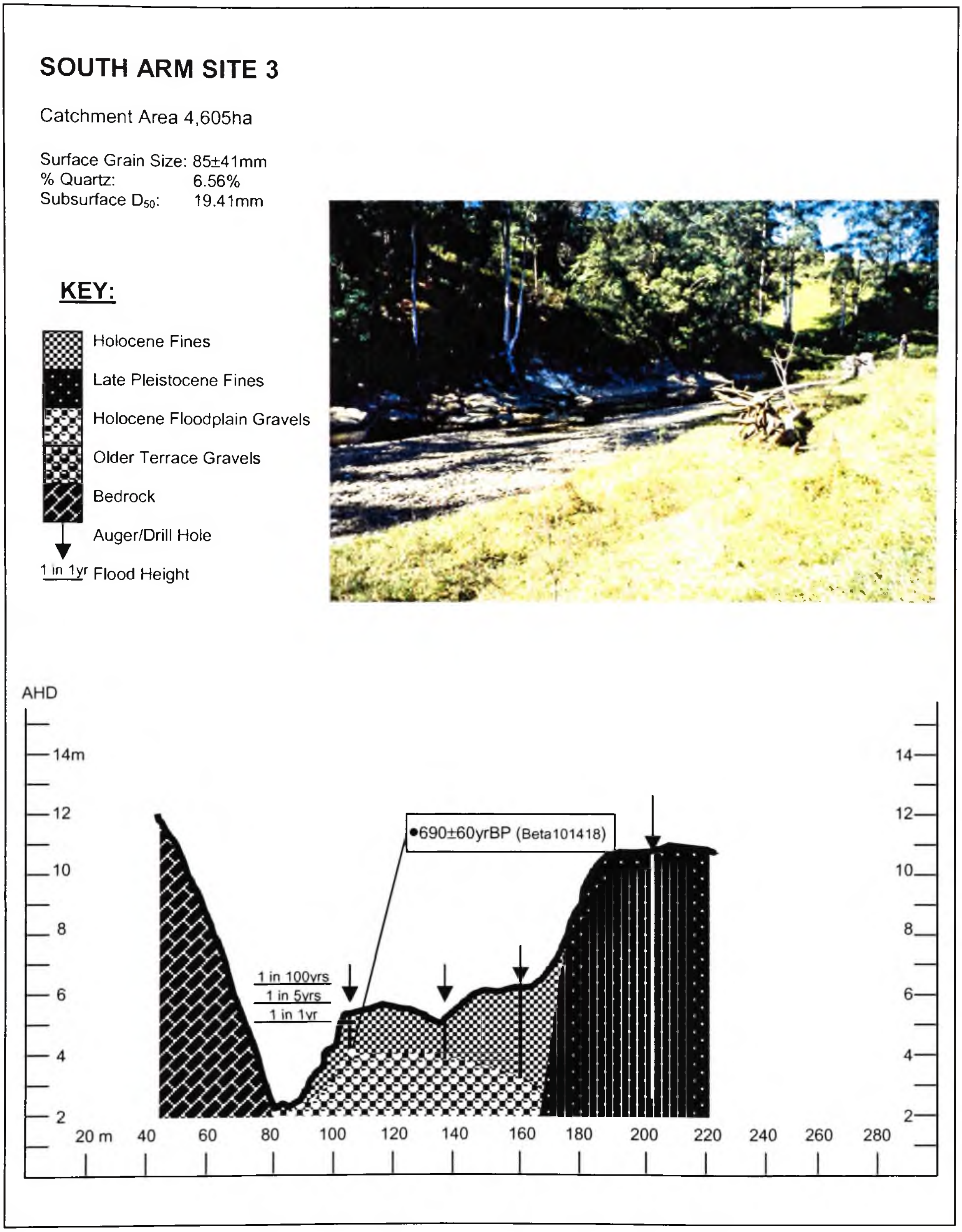


Figure 6.14: Stratigraphy, chronology and site photo – South Arm Site 3

SOUTH ARM SITE 4

Catchment Area 6,460 ha

Surface Grain Size: 37±15 mm
% Quartz: 35.00%
Subsurface D_{50}: 13.46mm

KEY:

Holocene Fines
Late Pleistocene Fines
Holocene Floodplain Gravels
Older Terrace Gravels
Bedrock
Auger/Drill Hole
1 in 1yr Flood Height

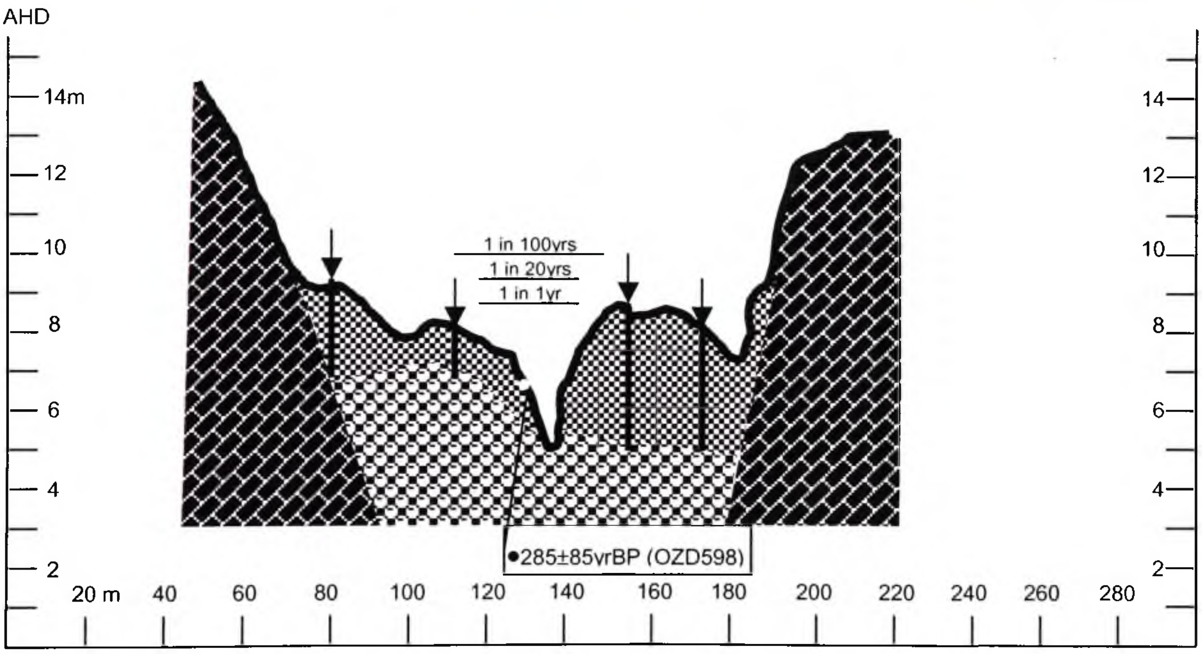


Figure 6.15: Stratigraphy, chronology and site photo – South Arm Site 4

BUCKRA BENDINNI CK SITE 2

Catchment Area 5,880 ha

Surface Grain Size: 41±19mm
% Quartz 44.26%
Subsurface D_{50}: 17.67mm

KEY:

- Holocene Fines
- Late Pleistocene Fines
- Holocene Floodplain Gravels
- Older Terrace Gravels
- Bedrock
- Auger/Drill Hole
- 1 in 1yr Flood Height

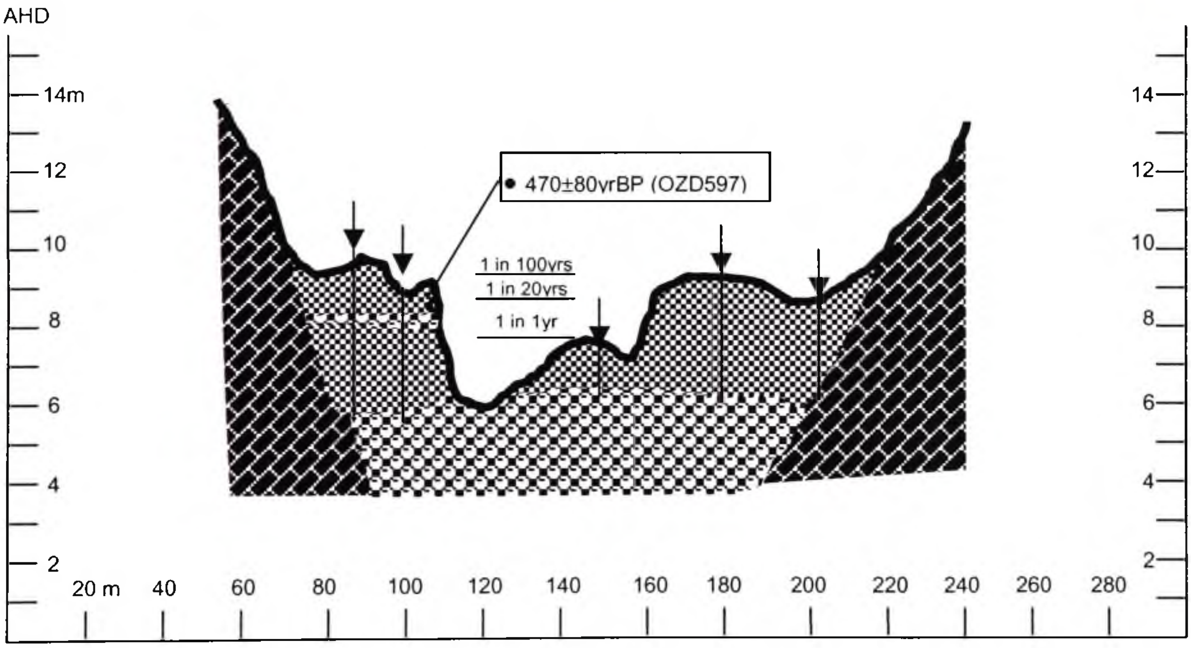


Figure 6.16: Stratigraphy, chronology and site photo – Buckra Bendinni Creek Site 2

6.3.4 Summary

In combination with TL ages derived from the terraces, there appears to have been substantial reworking of the Nambucca from OIS 5 (Colleambally) to the period after the LGM but prior to the Holocene (Yanco). The Holocene floodplains, however, all appear to be very young, <3000 yrBP.

The Holocene floodplain deposits that predated this period were confined between the Late Pleistocene terraces and appear to have been largely reworked. Laterally migrating channels from 12-3 ka laid down the basal gravels. After 3000 yrBP, the rivers the rivers apparently became laterally stable, forming narrow deep palaeochannels periodically avulsing and infilling with fines from 1500 to 130 yrBP.

A more detailed analysis of the Quaternary history of Nambucca catchment in the context of other NSW rivers is given in Chapter 7.

7. INTERPRETATION OF THE GEOMORPHIC HISTORY OF THE NAMBUCCA VALLEY

7.1 Late Quaternary Development of NSW Coastal Rivers

A summary of the geomorphology of NSW coastal rivers is given in Chapter 2 and this section builds on the information provided earlier. It is included to assist in putting the stratigraphy and chronology described in Chapter 6 in a regional context.

Figures 9.1 and Table 9.1 show the global periods of warmer and cooler temperatures (and higher and lower sea level) for the Late Quaternary geological period. On the basis of research to date, NSW coastal valleys appear to have erosional and depositional records that roughly correspond to these periods. While many papers have examined NSW sea level changes and estuarine depositional processes (eg. Thom and Roy, 1984; Hopley, 1987; Bryant, 1992; McMinn, 1992; Young et al., 1993), those dealing with coastal river environmental change during the Quaternary have developed a more limited data base (eg Warner, 1970; Young and Nanson, 1982; Nanson, 1986; Nanson and Young, 1987; 1988; Nanson et al., 1992).

Although there are no detailed studies of Quaternary changes on north-coast NSW rivers, the climatically induced flow regime changes of the Riverine Plain in the southeastern interior of NSW (Page et al., 1996; Page and Nanson, 1997) are now well understood. Changes on the Riverine Plain are seen to be very similar to changes recorded on the coastal Nepean River near Sydney by Nanson and Young (1988) (with the chronology being presently revised by Nanson and Price; work in progress). The Nepean River lies just 400 km south of the Nambucca catchment and their Quaternary histories probably exhibit broad similarities, as both the Nepean River and Riverine Plain show broad similarities with the Channel Country of western Queensland much further to the north and inland (Nanson et al., 1992). In the absence of a more local Quaternary record, those from the Riverine Plain and from unpublished observations on the Nepean River are summarised here as likely scenarios for conditions in the Nambucca catchment during the Quaternary, for it appears that there is considerable congruency in the middle to late Quaternary flow regimes for rivers in eastern Australia (Nanson et al., 1992).

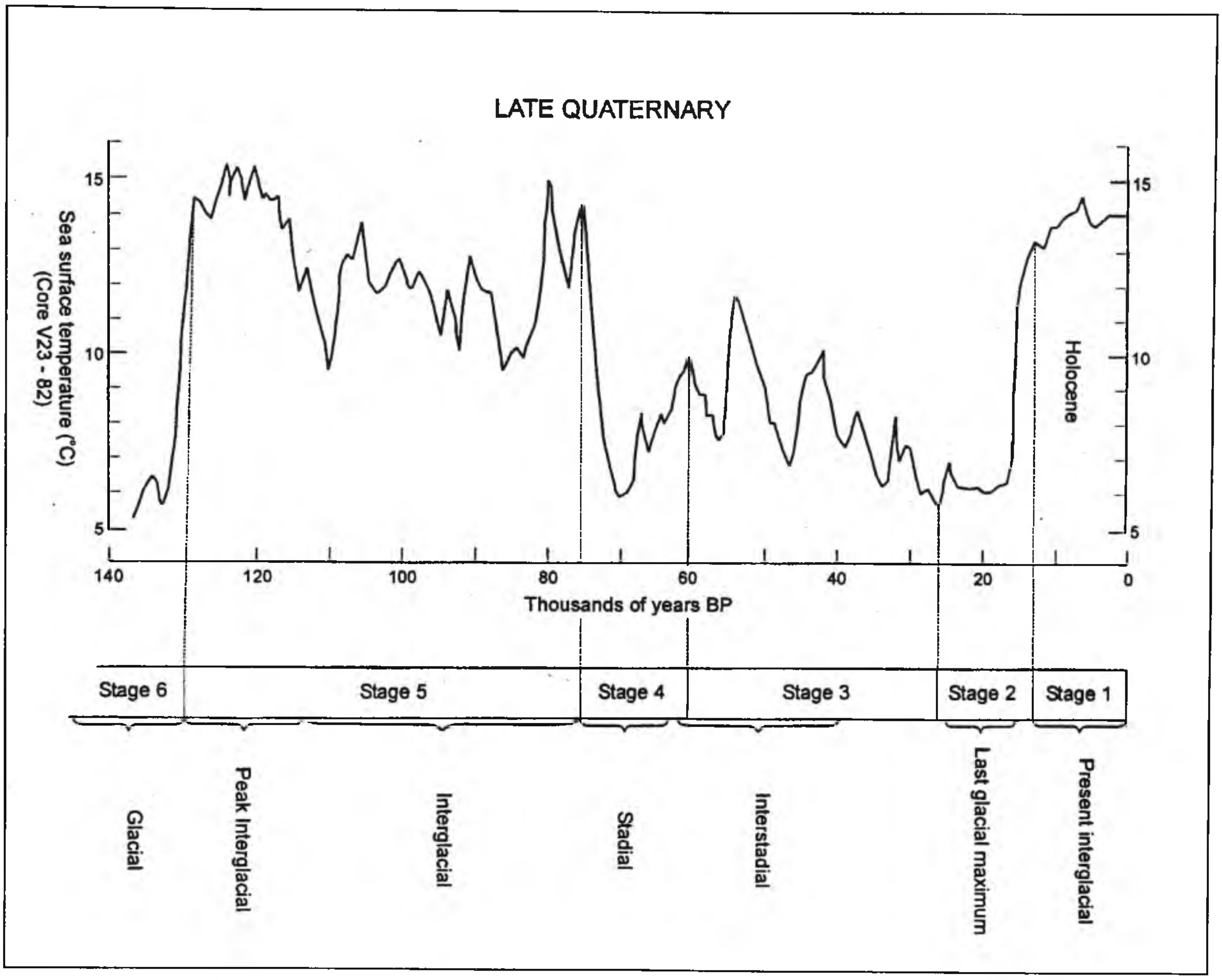


Figure 7.1: Sea surface temperatures and oxygen isotope periods in the Late Quaternary

Table 7.1: Phases of changing global temperatures from oxygen isotope analysis (Aitken, 1990)

Oxygen Isotope Phase	000's Years Ago	Climate	Approximate time of Max/Min Temp (yrBP)
1	0-13	Interglacial	9 000
2	13-32	Glacial	18 000
3	32-64	Sub-Glacial	50 000
4	64-75	Glacial	67 000
5	75-128	Interglacial	120 000
6	128-195	Glacial	155 000
7	195-251	Interglacial	215 000
8	251-297	Glacial	270 000

In this discussion it is important to recognise that the Nambucca catchment has never been glaciated. Glacials were times of low sea level corresponding with the glacial cycles and in the Australian context, glacials (or minor glacials, termed stadials) were relatively dry periods with interglacials (or less moderate periods, termed interstadials) relatively wet periods, although there was probably considerable variability within each of these (Nanson et al.1992). A description of periods of identified fluvial activity during Oxygen Isotope Stages (OIS) in southeastern Australia is given below.

OIS 5 - Interglacial (130-75 ka) – containing the Colleambally Phase (110-75 ka) in SE Australia: Conditions during the early part of this period in NSW are unknown, however from about 110 ka to 75 ka the rivers of both the Riverine Plain and Sydney region appear to have been high-energy systems transporting abundant sand and gravel; upland and coastal rivers were actively reworking their floodplains. The period of 110-75 ka is known as the Colleambally phase (Page et al., 1996; Nanson et al., 2003). The depositional record indicates greater run-off, higher and more extensive floodplains, coarser and more abundant sediment loads, and increased woody debris. The Nepean River at this time was transporting very coarse gravels and reworking its entire floodplain of many kilometres in width; it was probably braided in some locations (Nanson and Young, 1988). Sea levels were high relative to those during much of the Quaternary, but on average they were lower than at present, and climate was probable somewhat cooler reflective of larger ice volumes globally (Page et al., 1996).

OIS 4 - Stadial (75-60 ka) – containing no recorded period of fluvial activity in southeastern Australia : This appears to be a period of relative fluvial inactivity associated with a stadial (a small glacial) event, cooler temperatures than during Stage 5, and substantially lower sea levels.

OIS 3 - Interstadial (60-25 ka) – containing the Kerarbury (55-35 ka) and the Gum Creek (31-25 ka) phases in southeastern Australia: On the Riverine Plain the early part of OIS 3 (55 to about 40 ka) appears to have been about as active as OIS 5. On the Nepean River there was enhanced flow and overbank deposition between 60 and 50 ka and then a particularly active period with substantial, although not total, floodplain reworking between about 50 and 40 ka (Nanson & Price, in prep). The 55-35 ka period is known as the Kerarbury Phase (Page et al., 1996). On the Riverine Plain there was a further period

of enhanced fluvial activity prior to the Last Glacial Maximum (LGM) between about 32 and 25 ka (Gum Creek phase), but this event has not yet been identified for the coastal rivers. Sea levels during OIS 3 were probably higher than in OIS 4 and the climate warmer and wetter.

OIS 2 - Glacial (26-12 ka) – containing the Yanco phase (20-13 ka) in southeastern Australia: Sea levels were at their lowest point (declining to -130 m). In NSW the Glacial Maximum (24 to 20 ka) was relatively inactive, but immediately following was a period of enhanced activity on the Riverine Plain (20-15 ka), although it was less significant than either of the fluvial episodes in OIS 5 or OIS 3 (Page et al., 1996). During this period, high magnitude flows reworked the more vulnerable fine-grained overbank deposits along the Nepean River but did not extensively rework the coarse basal floodplain units. The period of fluvial activity from 20-13 ka in southeastern Australia is known as the Yanco phase (Nanson et al. 2003).

OIS 1 - Interglacial (Holocene 12-0 ka): Increasing sea levels gradually drowned the lower coastal valleys. A return to channel stability lead to the burial of coarse gravel floodplains with fine gravely and sandy floodplains in the reaches affected by sea-level changes. Above the influence of sea level variation, floodplains aggraded with overbank fines. In the absence of sufficient stream energy to rework entire valley fills in the last ~5 ka, some floodplains became dominated by autocyclic episodes of alluvial accretion and erosion (Nanson, 1986). Prosser (1987) dated periods of alluviation from 6,000 yrBP to the present in Wangarah Creek in the southeastern highlands of Australia, with a major phase occurring from 3,000 yrBP to 100 yrBP. Fryirs and Brierley (1998) also noted this timeframe as a period of major alluviation in the Wolumla Creek catchment on the south coast of NSW.

While it is not possible to recognise changes in flow regime during the Holocene epoch (the last 10 ka) with magnitudes comparable to those major events that have occurred in the past 100 ka, there is growing evidence that the early Holocene (between about 8 and 5 ka) was fluvially more active than the mid to late Holocene. Numerous terraces along much of the NSW coast date from this period (Hickin and Page, 1971; Warner, 1972; Blong and Gillespie, 1978; Melville and Erskine, 1986; Warner, 1992). Dodson (1986) obtained palynological evidence from Barrington Tops that suggests a slightly wetter

period between 8 and 5 ka, and Fryirs and Brierley (1998) found, on the south coast of NSW, that entire valley fills were excavated prior to about 6 ka and that alluviation has been the dominant process since then. Modern floodplains on the Macleay River (Walker, 1970), immediately south of the Nambucca catchment, appear to have cores dating from 5 to 3 ka, and there appears to have been a further reduction of fluvial activity since then with the development of inset floodplains in the Bellinger valley (Warner, 1992) on the Nambucca's northern boundary.

7.1.1 Significance of Quaternary Climate Change for the Nambucca Catchment.

On the basis of this summary, it would appear that the Nambucca catchment would have experienced episodes of considerable fluvial activity and sediment reworking several times in the last glacial cycle (the past ~130 ka). The last truly major episodes of alluvial reworking in the Nambucca catchment would have been late in Stage 3 prior to 25 ka, during which time entire valley fills (fans, terraces and floodplains) would have probably been replaced and from which time some of the oldest deposits remaining in the catchment will date. Indeed, the Nepean River terrace near Penrith yields dates for a period of major reworking between 50 and 40 ka and two of the oldest radiocarbon ages obtained from river terraces on the south and north coasts of NSW are about 29-34 ka (Walker, 1962; Warner, 1972).

Due to the confined nature of most streams in the Nambucca catchment, it is likely that even the relatively minor fluvial event recognised on the Riverine Plain and on the Nepean River after the LGM (i.e. at about 20 to 15 ka) was able to rework most of that basin's alluvium. Warner (1972, 1992) reports only a small area of Pleistocene terrace alluvium (dating at about 21 ka) remaining in the Bellinger valley. It must have been reworked by subsequent fluvial activity, particularly in the early to mid Holocene. From Warner's evidence in the Bellinger valley, many of the higher floodplains in the Nambucca catchment probably date from early to mid Holocene. The past 4 ka would have been a period of relatively stable forested floodplains with little alluvial reworking except for slow channel migration characteristic of many moderately active river systems, and for periodic and disjunct floodplain stripping and minor lateral erosion.

7.2 Pre-European Fluvial Activity in the Nambucca

7.2.1 Late Quaternary

Much of the previously published work completed on the fluvial geomorphology of the north coast of NSW has concentrated on the assessment of Holocene sediments (Warner 1972, 1992; Erskine, 1994; McMinn, 1992; Thom and Roy, 1984; Nanson, 1986). A great deal of the interpretation of Quaternary alluviation for southeastern Australia comes from the Riverine Plain (Page and Nanson, 1996), Nepean Valley (Nanson and Young, 1988) and Namoi Valley (Young et al., 2002). A synthesis of the pattern of Quaternary fluvial activity in the southeast Australian region has been compiled by Nanson et al. (1992) and Kershaw and Nanson (1993). The model coming out of these studies provide similarities in the discussion of the sedimentary patterns of the Late Quaternary.

The model put forward by Page et al. (1996) and Page and Nanson (1996) identifies four major sequential phases of palaeochannel activity commencing with the Coleambally phase between 105-80 ka. The following phases progress through the Kerarbury (55-35 ka), Gum Creek (35-25 ka) and Yanco (20-13 ka) phases until the start of the present fluvial regime about 13 ka. In a recent summary of fluvial activity on the NSW coastal rivers, Nanson et al. (2003) have encapsulated these phase names with specific references to the coastal rivers.

It appears that there is correspondence with the general picture of Quaternary flow-regime change on the rivers of NSW and that occurring in the Nambucca catchment. However, an analysis of terrace and floodplain chronologies in the Nambucca catchment reveals that there has been little preservation of sediment deposited since the end of OIS 5 (75 ka). This is not surprising, however, given the confined valleys and high-energy streams that are typical of coastal NSW. Prior to this study there have been no terrace dates at all from northern coastal NSW older than that found on Warrell Creek (78.1±6.5 ka). The nature of the channels and the differing underlying geology explain this preservation.

A series of terraces in the various tributaries of the Nambucca River have provided an important sequence of TL ages. The results from the 19 TL samples show strong

similarities with the alluvial chronologies provided from the Cranebrook Terrace in the Nepean catchment and Riverine Plain in the Murrumbidgee catchment. The limited preservation in the narrow Nambucca valleys has meant that just one OIS 5 TL result was obtained, an age of 78.1±6.1 ka (W2732) (probably Colleambally) from 6m depth in a 12 m high (measured from the stream bed) terrace at Site 3 on Warrell Creek. The survival of this large terrace is probably due to Warrell Creek being one of the least energetic of the seven sub-catchments within the Nambucca basin the fact that this catchment has the most cohesive clayey sediment (see Section 4.5.5). This late OIS 5 age agrees well with those from the Cranebrook Terrace and is not significantly different from the youngest OIS 5 ages on the Riverine Plain.

A single large terrace (10 m in height from the stream thalweg) at Site 4 on Taylors Arm provided three Stage 3 TL ages of 50.9±11 ka (W 2352), 52.9±4.5 ka (W2719) and 54.6±5.4 ka (W2718), a result supported by a basal date of 53.2±6.1 ka (W2349) for the northern terrace at Site 3 on Deep Creek. This marked a very prominent period of alluviation on the Cranebrook Terrace and for Kerarbury deposits on the Riverine Plain (Page et al., 1996), the Shoalhaven River (Nott et al., 2002) and immediately to the west on the Namoi River (Young et al., 2002).

The upper part of the northern terrace and the base of the southern terrace at Site 3 on Deep Creek provided late Stage 3 ages of 36.1±3.2 ka (W2727), 31.0±3.0 ka (W2728) and 25.5±2.1 ka (W2350) (Fig. 4). These correspond well to the full age-range of the Gum Creek Phase recognised on the Riverine Plain (Page et al., 1996). On the Kalang River (the southern tributary in the Bellinger catchment), Warner (1970,1972) identified an undifferentiated fluvial deposit at 34 ka BP that may also be from the Gum Creek Phase. Warner (1970,1972) also radiocarbon dated a terrace on the upper Kalang River at 20-21 k yrBP, a result supported by a recent radiocarbon sample from a buried terrace remnant on the adjacent Bellinger River, and preliminary OSL ages of 24-28 ka from the same unit (Cohen, in prep).

North Arm at Site 3 shows a substantial terrace unit that provided TL ages of 19.5±3.6 ka (W2724) and 16.2±1.2 ka (W2351), although possibly stratigraphically reversed, their errors show them not to be significantly different, suggesting a post glacial terrace of

similar age to the Yanco units on the Riverine Plain (Page et al., 1996). Evidence for the survival of substantial Yanco-age deposits in the Nambucca is supported by alluvial deposits that yield TL ages of: 20.9±4.4 ka (W2723), 16.2±2.1 ka (W2351) and 10.1±2.1 (W2722) at Site 6 in North Arm; 19.3±1.4 ka (W2726) at Site 5 in South Arm; 16.6±1.3 ka (W2721) and 15.4±1.3 ka (W2720) at Site 9 in Taylors Arm; and 13.4±1.1 ka (W2731), 12.6±1.1 (W2730) and 11.6±0.9 ka (W2729) at Sites 2 and 3 in Warrel Creek.

Large Gum Creek and Yanco-age palaeochannels, dated using TL and OSL, are present along the westward-flowing Gwydir River near Moree (Pietsch, in prep.) as are Yanco-age palaeochannels on the Namoi River (Young et al., 2002). Both are rivers immediately inland of the Nambucca catchment. Clearly, the Gum Creek and Yanco Phases of fluvial activity were characterised by much greater runoff and alluvial activity than occurs today.

Despite the limited preservation of older units in the confined Nambucca catchment, there is sufficient alluvial evidence to suggest that most of the late Quaternary fluvial episodes represented very clearly on the Riverine Plain and Nepean River are probably also represented in this narrow coastal valley in the form of terrace fragments. However, what the Nambucca basin has preserved relatively well is the story of alluviation following the LGM, particularly the radiocarbon chronology of alluviation in the late Holocene, which is discussed further in the next section.

7.2.2 Holocene

The early Holocene is not known to have been characterised by a particularly vigorous flow regime in the coastal valleys of NSW. As such it provides evidence of the *vulnerability* of the Nambucca catchment to relatively minor shifts in flow regime. As indicated by Young et al. (1986), Nanson and Erskine (1988) and Prosser (1991) and Prosser et al. (1994), the alluvial chronologies for coastal and near-coastal New South Wales indicate strongly episodic erosional-depositional events rather than a highly regular alluvial chronology indicative of marked episodes of climate change. This supports the threshold theory of Schumm (1973; 1977) that suggested individual catchments can experience dramatic changes while neighbouring catchments may be spared. The effect is a mosaic change superimposed on a pattern of more uniform

climatically induced episodes of deposition and erosion. Despite the 'noise' generated by episodic changes, similarities do exist, however, for the period of valley floor filling and floodplain reworking in coastal NSW. Evidence from a range of valleys along the coast suggest a marked period of valley alluviation and terrace formation between about 8000 and 5000 years BP (eg. Walker, 1970; Warner, 1972; Sullivan and Hughes, 1983; Melville and Erskine, 1986) followed by formation of the contemporary floodplains over at least the last 3000 years. In effect, most of the alluvial landforms affected by post-European disturbance are less than 3000 years old.

A total of 15 conventional radiocarbon samples obtained from floodplains throughout the Nambucca basin failed to date any Holocene-age deposits older than 3000 yrBP. The Holocene floodplains are commonly confined between Late Pleistocene terraces and appear to have been substantially reworked during the early to middle Holocene, leaving only basal gravels. From later in that period floodplains were overtopped with fine overburden of an even later Holocene age. In a recent synthesis this period of early to mid Holocene fluvial activity has been termed the Nambucca Phase (Nanson et al. 2003). It is acknowledged that for earlier episodes the presence of abundant alluvium is taken as evidence of fluvial activity, whereas here it is argued that its absence of floodplain alluvium between older resistant terraces is indicative of somewhat higher flows and enhanced flushing. While earlier Quaternary episodes were clearly major events that left substantial higher valley-side terraces, the Nambucca Phase was relatively minor and was probably only able to rework the confined floodplains between older terraces. Additional chrono-stratigraphic evidence based on 30 AMS radiocarbon samples within the Bellinger catchment (Cohen, in prep.) demonstrates channel stabilisation and the onset of vertical accretion following the Nambucca Phase. This occurred at approximately 4000 BP in the upper Bellinger valley and at about 3500-2500 BP (i.e. similar to the Nambucca catchment) in the lower valley.

At Site 4 on Missabotti Creek a gleyed organic clay within fine gravels gave an age of 2660±50 BP (Beta 101413). The fine overburden nearer to the surface at this site dated at 2330±50 BP (Beta 101412). Another example of a fine-grained floodplain is at Site 3 on Deep Creek, dating at 2080±60 BP (Beta 101421), with a clearly visible fine grained channel fill within the floodplain dating at 1580±70 BP (Beta 101419) and 1550±50 BP

(Beta 101420). In a similar situation at Site 5 on Taylors Arm, fine basal gravels dated at 1960±100 BP (Beta 101416) with sandy-silty overburden near the surface dating at 1020±60 BP (Beta 101417).

These sites show that most of the recent Holocene floodplains were formed with a fine gravel base and a vertically accreting silty overburden from about 2700 yrBP to the present. After about 2500-2000 yrBP there is no sign of lateral channel migration or other forms of substantial floodplain reworking or gravel accretion that characterised the Nambucca phase of the early to middle Holocene, suggesting that the channels became laterally stable at this time. Relatively narrow deep palaeochannels that date from about 1600 BP until the time of European settlement (around 130 yrBP) indicate periodic channel abandonment by avulsion. A well-defined palaeochannel in the floodplain at Site 6 of Taylors Arm gave a basal date of 130±60 yrBP (Beta 101414) while another palaeochannel at Site 4 on North Arm gave a basal date of 440±60 BP (Beta 101415).

The period from about 1500 yrBP until European settlement appears to have been remarkably stable, with infrequent channel avulsions but no extensive floodplain reworking. Within densely forested floodplains these laterally stable channels must have gradually constricted as a result of dense bank vegetation, and accumulations of LWD, and bank sedimentation with suspended fines. Channel fills located in floodplain sections on Deep Creek and North Arm (Figure 7.2) indicate narrow and deep suspended load channels filled with fine alluvium and undergoing periodic avulsion. Due to the slow moving water in the forest away from the new channel, silt would fall out of suspension and allow the old channels to fill with fines relatively rapidly. Further evidence that these channels probably aggraded their beds during this stable period is that recent destabilisation has resulted in channel incision associated with nickpoint retreat along extensive reaches.

Clearly, rates of alluviation in the modern floodplains can be variable. Dates from Taylors Arm (T5) show that 4 metres of sediment can be deposited in 1000 years, 3 metres of sediment on Missabotti Creek took 300 years to accumulate whereas on Deep Creek a 3 metre deep palaeochannel was half filled in less than 150 years. Hence, while abandoned channels can fill in relatively quickly, the floodplain building process may take

hundreds of years. Within-channel benches can form rapidly, yet the process of building an entire floodplain is much slower.

Once stabilised in the late Holocene, dense rainforest would have covered the floodplains and stream banks, undoubtedly cluttering the narrow channels with large woody debris, further reducing stream power already in decline due to widespread climate change. This condition would have led to periodic avulsion (Brooks and Brierley, 2002). The result was a highly stable late Holocene channel and floodplain system with some palaeochannel impressions. This is in stark contrast to the laterally active, floodplain-reworking systems that appear to have characterised much of the Late Pleistocene and probably early to mid Holocene. It was these recently stabilised channels, floodplains and palaeochannels, densely covered with rainforest, that the early settlers to the Nambucca and Bellinger catchments encountered when they cleared land for settlement in the mid-late nineteenth century (Nanson and Doyle, 1999).

Figure 7.2: Cut and fill sections on North Arm (Site N4) and Deep Creek (Site D3)

As with the modern streams, it is likely that the streams of the Nambucca catchment in the stable period prior to European settlement showed some differences between the upper, middle and lower valley reaches. In the upper catchment, dense vegetation and very coarse bouldery channel-boundaries would have limited bank erosion and gravel transport during and just after catastrophic events. It is likely that these channels remained oversized much of the time as channel recovery in such systems is not rapid, and powerful floods would have been sufficiently frequent to maintain a large channel form.

The upper-middle and middle reaches, with much finer basal alluvium, although dominantly stable, probably endured occasional catastrophic channel erosion and floodplain stripping. In a fashion similar to that which occurs today, the magnitude of large floods would exceed the erosional resistance of the alluvial boundary, especially if such floods were able to severely damage riparian vegetation and displace LWD. As discussed in section 4.5.4, the floodplain gravels in these middle reaches are, relative to channel gradients, more erosive than those up- and downstream.

The lower reaches would have had large total discharges, potentially eroding the finest grained gravels in the catchment. However, several factors would have lead to their relative stability. Firstly, it is quite possible that channel capacities declined downstream as has been recorded on Illawarra streams (Nanson and Young, 1981), or that at least they would not have increased greatly. Secondly, the floodplain widths available for routing and storage of overbank flows usually increase downstream while energy gradients become less and stream boundaries can become more cohesive with silt and clay deposition. Thirdly, although sediment sizes are low in these reaches, the energy gradient is proportionally less than in the middle reaches of the catchment. The net effect is that the uppermost and lowermost reaches above the tidal limit were probably more stable than the middle reaches.

There can be little doubt that LWD has played a dominant role in helping to reduce stream power, allowing the channels in the Nambucca catchment to stabilise prior to European settlement. Given that the channels would have been in the order of 50% smaller than the eroded modern channels, most full-size riparian trees would have straddled the channels upon falling. Such LWD can last more than 2000 years in the channel under exceptional circumstances (Nanson et al., 1995), and its accumulation,

even where not so resilient, is capable of greatly reducing channel capacities. It would also have been a factor in initiating channel avulsion.

Evidence of channel avulsion is prevalent in the stratigraphic record from about 1500 yrBP until European settlement. In the absence of prevalent channel migration, channel avulsions become the main mechanism whereby the channel responds to either a progressive decline in the efficiency of the existing channel (Brizga and Finlayson, 1990), or to a sudden blockage (Smith et al., 1989). Their presence in the recent stratigraphic record of the Nambucca catchment is further evidence of the general stability of the channels during this period.

Young et al. (2002) suggest a decline in the discharges on the Namoi River (immediately to the west) after about 6 ka. By the late Holocene the rivers of the NSW north coast had become laterally stable and were supporting riparian rainforest forest along their banks. However, during this period the floodplains continued to build by vertical accretion. These small, laterally stable and tree-lined channels with overbank fines are visible today in a few locations in the Nambucca, as are isolated examples of narrow pre-European palaeochannels.

This period of late Holocene fluvial stability following the Nambucca (12-3 ka) Phase appears to have been widespread on the rivers of southeastern Australia. Illustrative of its southward extent is that Nanson et al. (1995) have shown a very similar sequence of Holocene lateral activity switching at 3-2 ka BP to channel stability and vertical floodplain accretion on the Stanley River in western Tasmania. The timing of this shift in channel activity in different regions of southeastern Australia appears to be a function of local conditions as well as regional climate, but generally occurred between ~4000 and 2500 yrBP.

7.2.3 Summary

The sedimentary record obtained in this study for the Nambucca catchment contributes to those of the Nepean and Bellinger catchments to provide evidence of flow-regime changes in coastal southeastern Australia from about 100 ka to the present. While the data by no means provides a continuous or highly detailed record, they do supply

evidence for understanding the nature of changing fluvial conditions in the non-glaciated coastal river basins of NSW for much of the last glacial cycle. As such, this evidence allows direct comparisons with late Quaternary changes described for the westerly-flowing rivers of the Riverine Plain (Page et al., 1991; 1996; Page and Nanson, 1996).

Small catchments such as those of the Nambucca and Bellinger Rivers have experienced similar precipitation and flow-regime changes to those of the much larger rivers in eastern NSW. However, their confined nature means that they have retained only part of this record and have been particularly sensitive to Holocene changes less pronounced than those that occurred throughout much of the Late Pleistocene. Small remnants of alluvium from the dominant Coleambally and Kerarbury Phases have survived, suggesting that these were significant events throughout southeastern Australia. While the Yanco Phase (20-13 ka) had a relatively modest effect on the large rivers, it is widely preserved as the oldest major terrace system in the confined Nambucca catchment. The early to mid Holocene (12-3 ka - the Nambucca Phase) was marked by much lower flows than those of the Late Pleistocene, but they were certainly more pronounced than those of today. The confining effect of the Pleistocene terraces meant that much of the early to mid Holocene alluvium was reworked and therefore not preserved, although remnants do remain. Since about 3.5-2.5 ka many of the rivers of coastal southeastern Australia have been laterally stable with floodplains vertically accreting with overbank sediment depositing on or adjacent to well-vegetated channels (Figure 7.3). It was these low-energy, laterally stable rivers that European land clearance so dramatically destabilised within a few short years of settlement.

This broad summary of flow-regime changes on the coastal rivers of NSW in relation to changing climate is obviously open to considerable revision and refinement as more data become available, and as the significance of previous work becomes fully appreciated. Even though some rivers have shown great stability throughout much of the period since the LGM (Brooks and Brierley, 2002), major changes such as those recorded on the Nepean River and Riverine Plain are clearly the product of climatic forcing. The subtle changes recorded in the Holocene are in some cases difficult to interpret due to threshold and complex response effects (eg. Nanson, 1986; Prosser et al., 1994). Nevertheless, the evidence presented here shows that alluvium preserved along the rivers of coastal

NSW retains a strong climatic signature, albeit modified by local preservation potential and intrinsic thresholds.

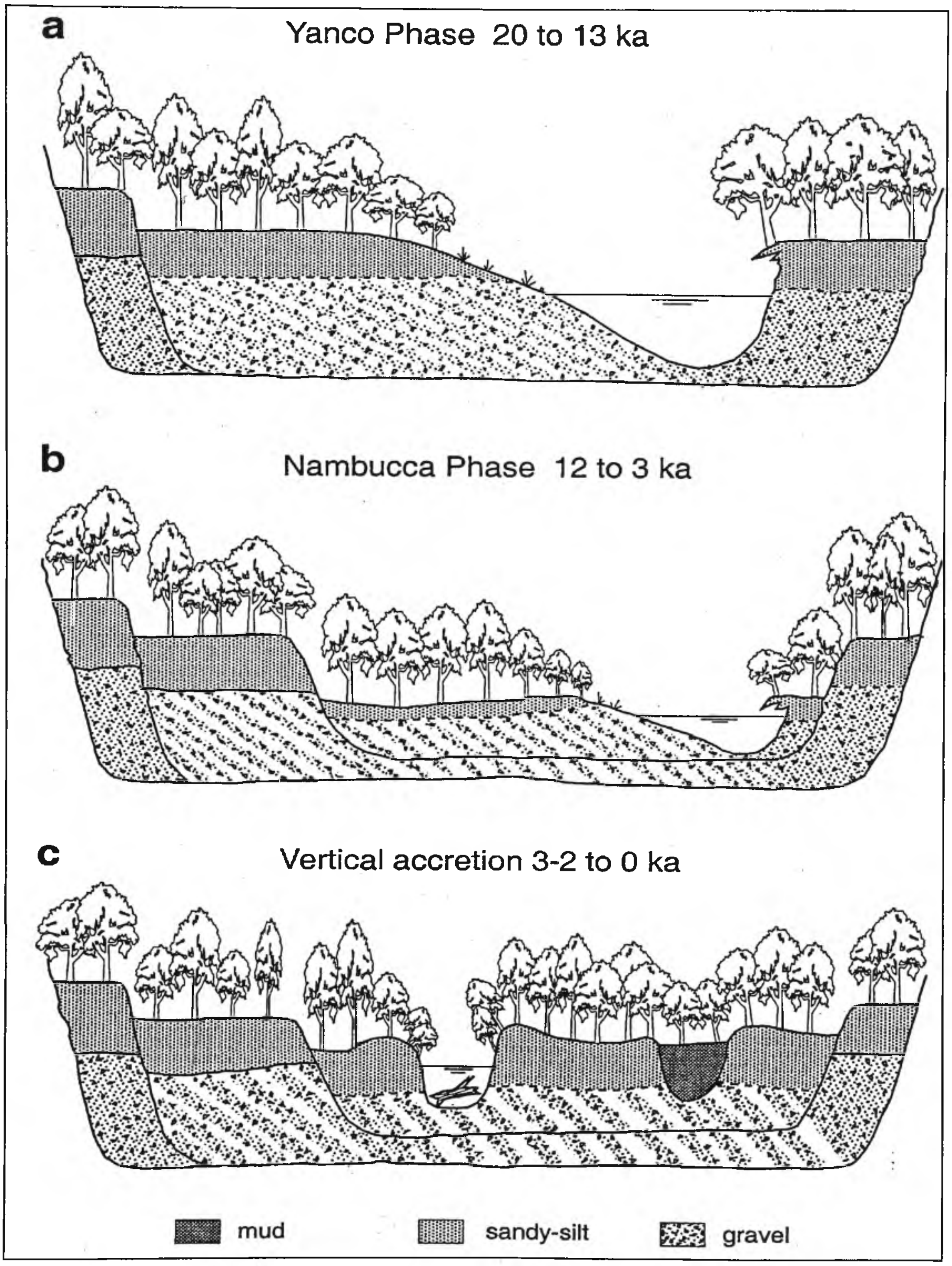


Figure 7.3: A schematic representation of floodplain and terrace formation in the Nambucca catchment

These sections are intended to represent the middle to lower valley, the boundaries are inferred, and the Nambucca Phase is based on very little alluvial preservation. The ages are in sidereal time for all periods.

7.3 Post-European Changes

Despite increasing amounts of research it is still difficult to establish exactly what the NSW coastal rivers were like at various stages through the Holocene and immediately prior to European settlement. Several lines of evidence are relied upon to interpret the pre-European conditions:

- *Firstly*, the upper and middle reaches of Warrell Creek and selected reaches of Deep Creek retain some original riparian vegetation and these locations appear to have largely undisturbed river banks and channel geometry.

- *Secondly*, the middle to lower reaches of Taylors Arm (T7-T9) exhibit sites that, although not completely undisturbed, do retain considerable native riparian vegetation and have what appear to be relatively undisturbed banks and channel geometries only slightly altered from pre-European conditions.

- *Thirdly*, the floodplain stratigraphies described above reveal a mode of floodplain formation and maintenance distinctly different from what is occurring today along most of the rivers in the catchment.

- *Fourthly*, recent observations along the Thurra River (Brooks, 1999c) has allowed a comparison between the Nambucca catchment and probably the last remaining river system in temperate to subtropical eastern Australia to retain essentially its pre-European forest cover and associated within-channel woody debris. Additionally, Cohen's (1997) study of nearby Jones Creek has shown what post-settlement disturbance of base level can do to even a densely forested catchment.

- *Fifthly*, comparison of the 1942 and 1991 aerial photographs reveals a pattern of channel change that can be considered retrospectively in order to gain some impression of the nature of the earlier undisturbed channels. This approach was adopted in Chapters 4 and 5 and is utilised again here to a limited degree.

After examining aerial photographs and historical accounts it is possible to identify four phases of change in the catchment since European settlement. These are based on settlement patterns and clusters of floods (Table 3.16) that combine to define phases marked by channel change or relative stability in the Nambucca

7.3.1 Phase 1 (1830-1870)

The first Europeans to dwell in the Nambucca catchment, albeit temporarily, were 'cedar-getters' who arrived in the 1830's through to the 1850's (Townsend, 1993). They practiced a form of selective logging, and although they cut some of the largest trees from the floodplains and river banks, they did not disturb the stumps of these large trees that must have continued to hold the alluvium together for years after the trees were removed. Unlike the early settlers who cleared tens of kilometres of red cedar in the lower Hunter (Haworth et al., 1999) the early Nambucca settlers were fewer in number and worked almost in isolation, discontinuing their efforts and leaving the catchment soon after (Townsend, 1993). By comparison with modern selective logging practices, their work would have been destructive in the areas in which they constructed snig tracks, haul roads and milling areas, and where they forded the many streams by battering down the banks. However, they made was no attempt to clear the land. Once they departed, the forests would have quickly recovered. Aided by a vast seed source so close to hand, small clearings would have reforested and exposed banks healed, and thus the rivers would have survived this first assault largely unaffected.

In the words of Townsend (1993, p. 31):

> "The earliest cedar-getters and traders of the Nambucca left little evidence of their presence on the river. The same is even truer of the pastoralists. The first pastoralists arrived in the 1840's, even attempting to settle as far into the catchment as Taylors Arm, however, these attempts failed and most of the middle catchment was not settled until the 1870's-1890's."

7.3.2 Phase 2 (1870-1896)

Serious land clearance for farming started in the catchment above the tidal limit in the 1870's. A few conditional purchases were taken up a few kilometres upstream of Bowraville in the late 1860's but it was not until the late 1870's and 1880's that purchases were acquired up Missabotti Creek at the confluence of Kennaicle Creek, up North Arm

and Buckra Bendinni Creek as far as Argents Hill, and Taylors Arm as far as Maloneys Creek, and even then only the better land was selected. For example, almost all of Taylors Arm above the tidal limit was still unoccupied by 1884. Undoubtedly, land clearance on the floodplains would have been rapid once settlers arrived, but it must have taken until the early 1890's before such activity would have had an appreciable impact on the rivers of the Nambucca catchment upstream of the tidal limit. As it happens, the early 1890's experienced a series of very large floods (there were 3 in 1890, including the largest on record, and a flood in each of 1893 and 1894). Prior to and during this exceptionally wet period, entire rainforest-covered floodplains, riverbanks and adjacent terraces would have been cleared by settlers. This series of floods was probably a major catalyst for the catastrophic channel change that would follow in the twentieth century.

It is not recorded as to what extent the stream banks were cleared, but at the time there was probably no compelling reason to leave them vegetated, despite Governor King's ordinance of 1803, which precluded clearance of vegetation within 10 metres of any stream, a law almost totally ignored by settlers (Raine, 1994). Gale et. al (1995) and Haworth et al. (1999) report an initial period of sedimentation in the New England Tablelands (west of the Nambucca catchment) that ^{210}Pb dates as being post 1860 and prior to 1916. This episode corresponds to the disturbance of the Nambucca recorded from 1870-1896.

A response to the removal of riparian vegetation would be a substantial reduction in bank strength and a dramatic increase in channel width. The gravels released from the floodplain would enter the stream as bed material and the fine sands and silts would either be relocated to floodplains as overbank deposition, or flushed through the system to the tidal channels and the estuary. The addition of gravels to the bed would exacerbate the problem of stream-bank erosion, as an increase in coarse bed-material itself causes additional channel widening. Velocities would increase as the removal of trees along the channels terminates the supply of much of the LWD that enters streams in forested areas as a result of natural tree-fall, and this debris offers natural resistance to flow. Furthermore, widening of the channels would mean that previously emplaced logs become outflanked causing them to be washed downstream.

Experiments in clearing small catchments in the Australian Highlands showed that subsequent to clearance, a storm expected to produce peak flows of 60-80 m^3/s in a forested catchment, produced a peak flows of 370 m^3/s, a 500-600% increase (Goudie, 1993). This type of increase in peak discharge exceeds any known precipitation increase in recorded history, and while the effects on the much larger Nambucca catchment would not necessarily be so dramatic, such increases in the tributary basins would affect local erosion and sediment supply to the trunk streams.

While it is presumed that much of the Nambucca catchment would have remained forested by the 1890's, with only the floodplains extensively cleared for farming, the efficiency of flood routing along these cleared floodplains and channels would have been considerably improved. The 1890 flood, the largest on record, occurred right at the time of maximum forest clearance. Higher flow velocities, decreased bank strengths from vegetation removal, and a clustering of large floods would be sufficient to cause the stream of the catchment to readjust rapidly. Corrasion of bank material, which may not have had time to properly recover from previous floods, would have been enough to allow LWD to be outflanked and removed. Subsequent flows would have then scoured the riffles, previously held in place by the LWD, and deposited this sediment in the downstream pool or series of pools. The net effect would be a substantial reduction in roughness and an increase in average velocities.

Despite the coincidence of land clearance and exceptional flooding early in the settlement period, it is likely that erosion then subsided as much of coastal NSW endured a remarkably dry and inactive fluvial period for the next 40-50 years (Pittock, 1975; Cornish, 1977; Erskine and Bell, 1982; Erskine, 1986, Nicholls and Lavery, 1992).

7.3.3 Phase 3 (1897-1947)

During the half-century from 1897 to 1947, the Nambucca experienced very few floods over 8.0 m at the Bowraville gauge. It is possible that the long-term impact of 1890's floods was partially mitigated for a number of years as a result of a lack of subsequent major flood events. In other words, the river was prevented from making a complete transition to its fully modified "rural form" until the next flood-prone period in the latter half of the twentieth century. Although there would have been pressure on the catchment from the intensification of dairy farming, a lack of closely spaced major flood events

meant that there was no mechanism to undermine the banks and cause channels to shift laterally. Floodplain gravels, therefore, would not have been released into the system in large quantities.

As an erosional episode, Phase 3 appears to have been relatively minor. However, as there are no aerial photographs or documented evidence of stream changes prior to 1942, comparative degrees of change are difficult to decipher. The 1942 photographs taken at the end of Phase 3, indicate that many reaches had a dry, grassed stream bed in some riffle sections (eg. around N5) whilst other sections appear overwidened with excessive gravel deposited (eg. M3) and *Casuarina* colonisation underway on these bars. A series of meander cut-offs was evident on lower South Arm by 1942. However, there is little other evidence of nickpoint retreat and channel incision up until this time.

Belief probably grew among residents that the Nambucca River, although not the same as a within-forest stream, was an essentially stable system and that it could be expected to remain much as it appeared at that time. Several long-term residents recall swimming and fishing as children in long deep pools in the river in the 1940's, pools they say disappeared in the 1950's to 1970's. In fact, this stability was a hiatus, simply the product of the flood-reduced flow regime of that period. The 1942 aerial photographs show the rivers as they were at the end of Phase 3. The channels were clearly very much larger than would have been the case for the within-forest streams prior to European settlement. Their beds consisted of extensive gravel bars and in places there were scalloped banks indicating some bank collapse. However, because of a lack of frequent channel-modifying floods, it is clear that the active channels were considerably narrower than the present ones, they were more sinuous, there were trees in places growing on the beds, and pools remained in many locations where there are none today. In other words, they appeared as a severely degraded channels but still with some of the characteristics of their within-forest precursors.

There is, however, some evidence for fairly substantial local reworking of gravel deposits pre-1942, particularly on Missabotti Creek, where gravel splays are evident below the bridge at Site M2. In keeping with the degree of instability that was to follow, the greatest extent of change occurring during this phase was experienced in the middle reaches of Missabotti Creek and to a lesser extent on the middle and upper reaches of North Arm.

The 1942 aerial photographs also indicate this change occurred on middle and upper reaches of South Arm and Taylors Arm. The middle and upper reaches of Buckra Bendinni Creek may have experienced some instability, although there was further degradation here post 1942. During Phase 3, many of the channels were primed ready for greater disturbance, which came with the next phase of flood-dominated conditions.

7.3.4 Phase 4 (1948-Present)

Just as it was a series of floods in the 1890's that probably initiated Phase 2, a series of 6 floods registering over 9m at Bowraville between March 1946 and February 1954 almost certainly initiated a second phase of erosion in the form of channel incision and lateral expansion. Anecdotal evidence indicates that the June 1950 flood, in particular, delivered an enormous amount of gravel to the channel. Channel erosion proceeded throughout this phase to different degrees at different times and in different parts of the catchment as nickpoints migrated. Resources Planning (1989) show evidence of bed lowering from comparative cross-sections between the 1960's and 1989 (Appendix 9). In some areas the channels became extremely wide and massive gravel bars were deposited. Many of these gravel bars were extracted after the 1950 flood (J. Argue pers. comm., 1996). The resultant channel was wide and only slightly entrenched.

An increase in rainfall, channel capacity and sediment transport between 1949 and 1955 was reported in the Macdonald (Erskine, 1986), Hunter (Erskine and Bell, 1982) and Bellingen (Warner 1987; 1992) valleys. Warner (1982) indicated that the mean annual flood ($Q_{2.33}$) in the period 1900-1950 was 350 m^3/s whilst the mean annual flood after 1950 was 800 m^3/s. This phenomenon was reported for most coastal valleys in NSW (Erskine and Warner, 1988). Channel expansion resulting from the 1949-1955 sequence of floods resulted in channel banks and bed margins consisting of exposed gravels.

These altered conditions and exposed gravel bars were ideal for colonisation by the opportunistic species *Casuarina cunninghamiana*. Evidence from the 1942 and 1991 aerial photographs shows that it colonised the river in this period, proliferating on bare banks and gravel bars. This colonisation, in conjunction with extraction of gravel from point bars, meant that the *Casuarina cunninghamiana* proliferated at a height close to the channel bed. Exposure to relatively low flows enhanced the chance of divided flow and

island formation as *Casuarina cunninghamiana* locally stabilises the gravel bed, but flow can pass around these tree colonies and scour secondary channels, leaving the stand of casuarina trees as an island. *Casuarina cunninghamiana* is known to have proliferated on the New England plateau, adjacent to the western drainage divide of the Nambucca (Gale and Pisanu, 2001). Clearance of wet sclerophyll and rainforest from the channel banks and floodplains of the Nambucca catchment, would have presented conditions ideal for this opportunistic species.

While the incision started in the lower reaches of South Arm, nickpoint migration up South Arm has been a much slower processes than in North Arm and Missabotti. The reason for this probably rests with the nature of the bedload in these two systems compared to South Arm. Nevertheless, nickpoints are gradually proceeding up South Arm, and are now well into Buckra Bendinni Creek. It is interesting to note that by 1991 nickpoints had proceeded up Buckra Bendinni Creek beyond the confluence with South Arm. Tributaries flowing into South Arm are also experiencing base lowering (see Figure 8.7) indicating that nickpoints have indeed migrated up this Arm.

In addition to the dramatic hydrological change that occurred in the later half of this century, it is noteworthy that the availability of mechanised equipment greatly increased after World War II. This could have influenced the extent to which official and unofficial channel modification works were conducted, and affected the rate at which gravel was unofficially extracted from the channels. However, there are no figures available to support this contention. Certainly, the removal of channel and bank vegetation in the form of dead snags and large trees within the channel using mechanised equipment (eg. In the form of a government approved 'Red Scheme' in the early 1970's) would have contributed to increased flow velocities and bank erosion on those reaches directly affected.

7.3.5 Summary

European settlement and land clearance has caused the Nambucca system to adjust catastrophically (Figure 7.4). The effect of floodplain and hillslope clearance would have greatly reduced flow transmission times by increasing channel and floodplain velocities, and thereby increasing peak flood-discharges. Land clearance would have also

increased valley-side erosion and amount of hillslope sand, silt and clay entering the streams. However, this would have been short lived, for pasture grasses once established are very effective at preventing slope wash, and there is little evidence of gullying on the valley sides. Undoubtedly, the most important source of silt, sand and gravel for the channels was widespread enlargement of the channels themselves. Furthermore, the stability of the upper-most reaches of most streams in the catchment, and Missabotti Creek is an excellent example, is sufficient evidence that gravel is not being derived at present from the headwaters. Vegetation clearance from the stream banks, the removal and decay of LWD, gravel extraction, channel realignment, and removal of vegetation from the hillslopes have all contributed increased flow velocities and discharges and, therefore, to channel expansion and excessive sediment transport.

Clusters of large floods are the triggering mechanism for channel erosion in disturbed catchments such as the Nambucca. A series of large floods in the 1890's would have almost certainly initiated channel expansion. The removal of LWD, the excavation of gravel from riffles and channel realignments would have initiated the movement of nickpoints upstream and the bank collapse that follows such channel deepening. It is also probable that some 'natural' meander cut-offs were initiated at this time, for the 1942 aerial photographs show cut-offs that were relatively young at the time of photography. The 1948-1965 floods, particularly those early in that period, initiated the second major wave of channel change. In the intervening period between the 1890's and the late 1940's, there were no significant clusters of flood events and hence after each individual large flood there was time for vegetative recovery before the next flood.

Historical records indicate extensive dredging in the tidal reaches from the 1920's, particularly around Bowraville where shipping was important. The disturbance to the channel bed from dredging could have been enough to initiate bed lowering upstream. Whilst the flood events at this time were not as frequent as at other periods in the historic record, single events can still cause major changes to the channel bed. Such changes could have triggered a series of meander cut-offs in lower South Arm just prior to 1942, or at least furthered the channel degradation initiated in the 1890's.

The period of repeated flooding between 1946 and 1954 (with numerous floods in 1950) led to dramatic changes in the Nambucca. The spacing of these floods meant that

vegetative recovery in the channel between floods could not be maintained. Anecdotal evidence suggest that there was a 'flood wave' on Missabotti Creek as a 'wall of water' had moved downstream in 1950 (C. Gorely pers. comm., 1997). Associated eddying eroded the bed and banks, mobilising large amounts of soil and gravel stored in floodplains and cumulating in the deposition of wide and high bars in the channel.

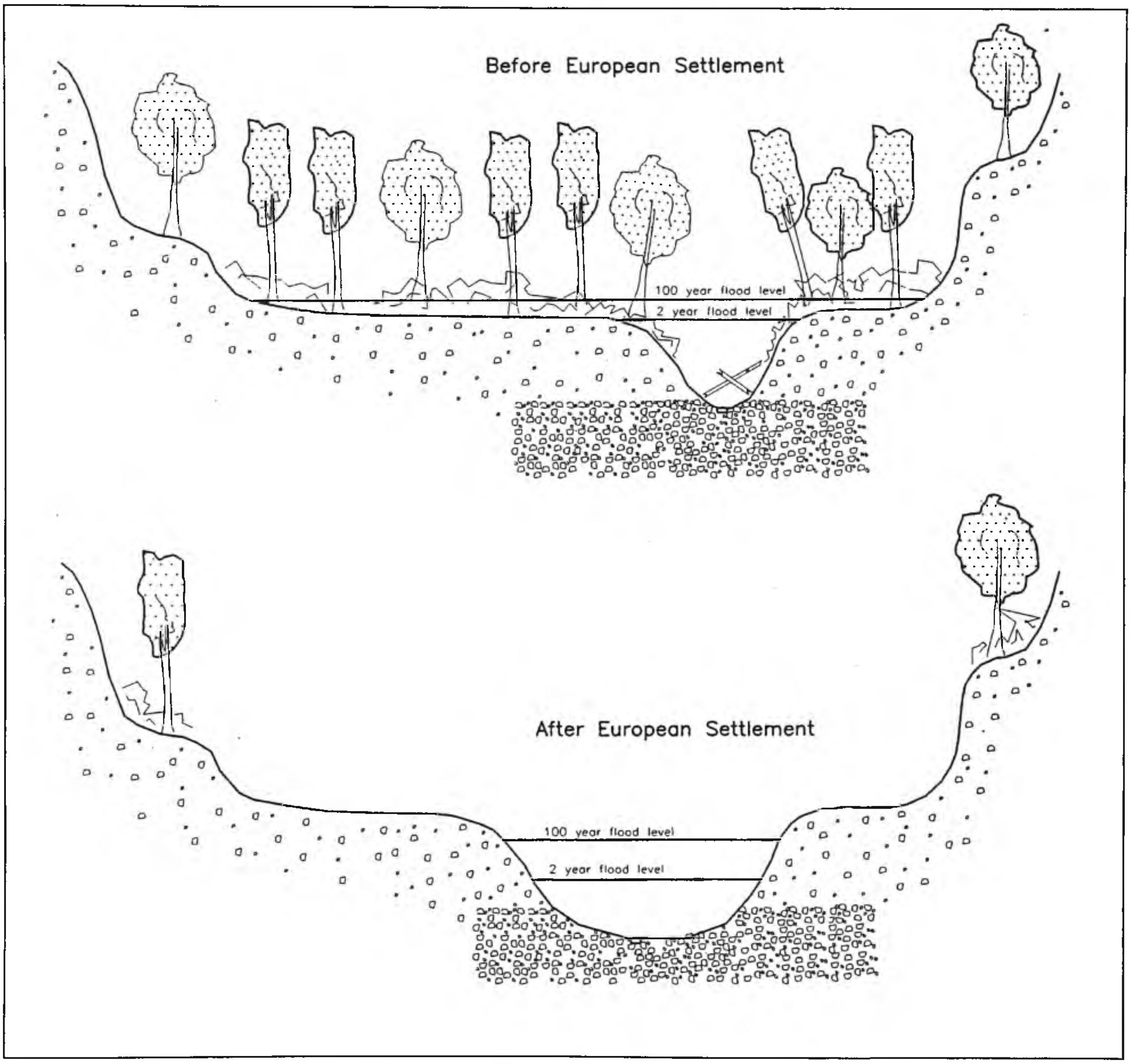


Figure 7.4: Typical channel and flood conditions before and after European settlement in the Nambucca catchment

Any ancient woody debris that had survived and supported riffles up to that time were almost certainly eroded. Channel widening, meander cut-offs and bed lowering occurred later as nickpoints retreated up the valley. Massive bars that appeared as a result of these large floods was mined for gravel, thereby maintaining channel enlargement. In natural streams gravel bars are built after major erosional events and the height of these bars can allow the subsequent floods to deposit silt on top, an important process in re-establishing the floodplains. The removal of high bars means that the floodplain building and stabilisation process cannot be initiated and the stream is allowed to wander in an overwidened and over deepened 'trench'.

As nickpoints moved upstream, damage from the 1950 floods failed to be repaired in the years following. Lowering of the streambed enabled erosion of gravel that was previously inaccessible to stream flow. This process began the parallel retreat of banks in straight reaches as well as the accelerated erosion of banks on the outside bends, processes that have worsened until the present day. The widening of the main channel allowed conditions for *Casuarina* to proliferate on stream banks and bars within the channel. These trees were probably largely unrepresented in the headwaters and middle reaches of the catchment until clearance of the original floodplain vegetation that consisted of dense wet sclerophyll forest and rainforest. Their proliferation along the streams appears to have been a recent phenomenon. Some tributaries (eg. Kennaicle Creek) do not have any substantial *Casuarina* colonies as yet. Uninhibited growth led to further erosional problems but as pointed out in Chapters 5 and 8, these trees only grow in response to channel disturbance.

In the 1970's, as a remedy for bank erosion and inundation of floodplains, the 'Red Scheme' saw the removal of a lot of in-stream vegetation, woody debris and bank vegetation. This practice had the desired effect of mitigating floods but the undesired effect of causing greater erosion and within-channel flood damage. Not surprisingly the focus of departmental reports in the Nambucca a decade later was bed and bank erosion and not flood mitigation. However, the unabated extraction of gravel in the 1980's in particular did nothing to help the channels restore sinuosity, build floodplains or restore bed elevations (Figure 7.5).

The pre-European channels meandered through the floodplain material much more than the current system which is dominated by straight reaches flowing in a straight line from one valley side to another, eliminating the meandering that was evident in the past. Apart from localised bed degradation, the velocities on the downstream side of the straight reach has caused serious erosion and overwidening. Examples of this exist on Buckra Bendinni Creek and Taylors Arm (Figure 8.10).

Figure 7.5: An example of illegal gravel extraction from North Arm in the late 1980's

A review of the observations on post-settlement change are given below:

7.3.5.1 Stability Prior to European Settlement

Radiocarbon dates from the Nambucca floodplains indicate that the last significant period of floodplain reworking ended between 3000-2500 yrBP. From then until European arrival the system was very stable with any changes associated with infrequent channel avulsion. By comparison with today's system the channels were sinuous with wet

sclerophyll and rainforest vegetation ensuring bank strength and a source of LWD to retard velocities, support bed levels and maintain pools and riffles. All of the above conditions acted to slow floodwaters and allow vertical accretion to take place on the floodplains.

7.3.5.2 Effects of Initial European Occupation

Vegetation clearance began in the 1860's, but much of the selection of land upstream of the tidal limits took place between the 1870's and 1890's. The initial effects of settlement were the clearance of bank and floodplain vegetation and more gradually, the decay and removal of LWD in the channels. These effects would have lead to increased run-off, reduction of in-stream roughness, and the mobilisation of bed material. A clustering of flood events in the 1890's was probably the first trigger for major change. A sedimentary record of disturbance after 1860 and prior to 1916 has been recorded by Gale et. al. (1995) and Haworth et. al. (1999) along the divide in the New England Tablelands, and this indicates anthropogenic impacts were having environmental impacts in the late nineteenth century in southeastern Australia. As the population of the district increased, so too did the use of the river and its floodplains. A lack of successive large floods until the 1940's has meant that relatively isolated instances of channel instability partially recovered by the time the next flood came. However, the 1942 photos show that the floods in the first half of the twentieth century were still sufficient to cause and maintain a degree of channel expansion, probably exacerbated by the on going removal of LWD and bank vegetation, and dredging, gravel extraction and artificial channel straightening.

7.3.5.3 Catastrophic Change in the 1950's

A series of large floods during the 1940's and 1950's proceeded to cause major erosion in the catchment. Contrary to some local opinions, the channels were already degraded prior to 1950, but not as severely as at present. However, the series of floods at this time were noteworthy not only for the duration of the floods, which saturate the banks and floodplains to a level where further high velocity flow can cause mass failure, but also because anecdotal evidence suggests that 'flood waves' were responsible for much of the damage in the June 1950 flood in particular. Such a flood wave would be capable of uprooting woody debris from within the channel bed. Subsequent removal of the gravel bars by landholders and the lack of replacement woody debris entering the system

contributed to the continuation of stream degradation. From resident surveys and discussions with landholders, the series of floods in the early 1960's (four of the largest floods on record in only two years) worsened stream conditions, as did floods in 1989-1990. The removal of riparian vegetation and the clustering of flood events seem to cause much more severe channel erosion than does any recognisable sequence of FDR/DDR cycles.

7.3.5.4 Resistance to Erosion of Deep Creek and Warrell Creek

Geology different to the remainder of the catchment and a lack of stored floodplain gravel accessible to the present channel has been instrumental in the preservation of upper and middle Deep Creek and all of Warrell Creek. Auger hole data indicates that there is no gravel down to the present water table at the channel margins. The riparian zone appears to have been densely vegetated throughout the post European history of these valleys, an important additional factor in their survival. Lower Deep Creek has begun to erode though due to bed lowering which has exposed gravels at the base of the river terrace and is undercutting the terrace. A similar fate could await Warrell Creek if the channel were allowed to incise below the current water table where stored gravel may be present.

7.3.5.5 Erosion in the Middle Non-Tidal Reaches

The middle reaches of the non-tidal streams of the Nambucca catchment are the most degraded (eg. T3-T5, N2-N5, M1-M4, B2, S3). A combination of factors has led to this situation. Gravel small enough to be readily entrained, and gradients steep enough to implement such transport, has probably always made the middle reaches more active and prone to geomorphic change. The floodplains are at their widest in these reaches and the stratigraphy displays fluvially derived gravels encompassing the entire width of the floodplain. In recent times decreasing sinuosity has led to the channels moving from one valley side to another in a more direct line. Because of the decreased sinuosity and reduced in-stream roughness, gravels are entrained from the toe of the banks by stream flow moving at velocities higher than previously experienced. Floodwaters are confined to the enlarged channels thereby concentrating erosional energy.

7.3.5.6 Causes of Bed Lowering

Extensive bed lowering in the Nambucca is the result of a number of contributing factors. The loss of LWD from initial channel clearance would have been the first major factor. Dredging of the lower reaches, up to Bowraville, could also have caused nickpoint retreat, particularly the head cut that had retreated up South Arm that is evident from the 1942 aerial photographs. In more recent times bed lowering has continued due to meander cut-offs (human induced or otherwise) and gravel extraction from the channel bed. Once the channels start to enlarge, they retain higher discharges and erosion worsens. Numerous smaller tributaries are currently experiencing nickpoint retreat in response to base level lowering of the trunk channel. These tributaries are often located in the upper reaches which gives an indication of the extent to which bed lowering, localised or systematic, has occurred

7.3.5.7 Source of the Gravel Influx

Fieldwork has indicated that the source of excess gravel in the channel is from channel widening and bed lowering. The source of the gravel is not from the headwaters as the dominant geology in the headwaters is phyllite and the lower reaches contain quartz gravel. The headwaters, on inspection, are also quite stable and are not providing large amounts of bed material to the lower reaches. This is evident at the top of Missabotti Creek where there is a large store of gravel in the floodplain, considerably finer and more readily transported than the stored gravel found in the headwaters of the other tributaries. Despite this, the headwaters of Missabotti Creek are essentially stable, as revealed by the stability of the scour pits in the uppermost reaches. The danger of erosion in these reaches does not come from upstream but from a retreating nickpoints found downstream. Evidence for the in-stream gravel coming from the eroded floodplain is the similarity in gravel size between the current bedload and adjacent floodplain deposits.

7.3.5.8 Loss of Pools

Initially, the loss of pools in the Nambucca arose due to riffle erosion at the downstream ends of pools. By a combination of nickpoint retreat and the loss of LWD the pools began to infill, resulting in a more uniform bed profile. This meant that the now shallow pools ceased being areas of energy dissipation. Increased velocities at valley sides from overwidening, and a lack of pools for energy dissipation, would threaten erosion of inner

bends from; (a) deflection of high velocity flows from the valley side to the inner bend or, (b) overwidening causing the radius of the meander curve to be less than twice the width ($R_C/w < 2$). Once the pool has become overwidened there is insufficient concentration of stream flow energy to scour out another pool.

7.3.5.9 Role of Vegetation

There has been an increase in the extent of riparian vegetation, primarily river oaks, since 1941 in the Nambucca catchment. Much of this increase has occurred at the same time as dramatic increases in channel instability, leading many to assume a causal relationship. However, river oaks or other riparian species, have not caused the instability within the streams of the Nambucca catchment. River oaks are a primary colonising riparian species whose preferred habitat is newly exposed gravel bars. The expansion in the extent of river oaks is largely a response to the channel instability - i.e. there has been an increase in habitat suitable for colonisation by such a species. In channels subjected to major bed lowering associated with nickpoint retreat, bank erosion (i.e. channel expansion), is an inevitable consequence. Whilst it appears that this species has exacerbated bank erosion by flow diversion, due to gravel bar colonisation and fallen trees, they are not responsible for bed degradation - the major cause of accelerated erosion. Few riparian species will remain standing under these circumstances, because their root system is inevitably undermined. Some species will submit before others, but all will go eventually. When substantial bed degradation occurs, the channel will adjust to similar dimensions whether it is grass or a fully forested flood plain. The difference between the two extremes of a fully grassed and an extensively forested riparian zone, is in the recovery process after the bed degradation has occurred. Under the forested scenario the channel becomes filled with LWD. Locally this may cause bank scour, which in turn may lead to increased sinuosity, but this is a necessary part of channel recovery following such instability. However, a large volume of LWD imposes a negative feedback on the system - aiding bed stabilisation and aggradation, and leading to re-stabilisation of the fluvial system.

8. MANAGEMENT OF THE PROCESSES AT WORK IN THE NAMBUCCA CATCHMENT

8.1 Fluvial Processes at Work in the Nambucca River Catchment

The 1942, 1964 and 1991 aerial photographs document nearly 50 years of bank erosion, decreasing channel sinuosity, lateral channel-migration, channel expansion, nickpoint migration, bed lowering, pool infilling and vegetation changes along the channels of the Nambucca catchment. Identified changes over this period provides evidence for past change and patterns that will affect the immediate future.

There has been considerable variation in the degree of channel instability in the eroded central tributaries of the Nambucca catchment since 1942. The least stable reaches include almost all of Missabotti Creek and the middle reaches of North Arm, with the most stable being the lower (eg. T7-T11) and upper reaches (eg. T1-T2) of Taylors Arm (see Figure 4.11). In general terms, most of these five tributaries exhibit the greatest deterioration in the middle reaches. Specific examples of channel deterioration between 1942 and 1991 are outlined in the following sections.

8.1.1 Meander Cut-Offs, Reductions in Sinuosity and Channel Widening

An examination of the effects of meander cut-offs and channelisation on the Latrobe River in Victoria by Reinfelds et al. (1995) found that there had been a 25% reduction in channel length since the late 1800's. Associated with this was channel incision of up to 1.05 m and a 67% increase in channel capacity with an associated threefold reduction in overbank flow duration. The effects of channelisation are well documented worldwide (eg. Keller 1975; 1978; Brookes, 1988).

Natural and artificial straightening of streams is visible in the Nambucca catchment aerial photographs and these changes have substantially shortened and widened channels in the Nambucca catchment. From the 1942 and 1991 aerial photographs clearly defined cut-offs can be recognised as having occurred near M3, M4, S5, T4. An artificial cut-off, which has resulted in spectacular channel instability, can be seen at Argents Hill (N3) and this was undertaken in the 1980's. A reduction in channel length, and a roughly

equivalent increase in local gradient, has produced an over steepened reach that is proving very difficult to stabilise.

A series of six cut-offs prior to 1942 on South Arm between S4 and the tidal limit has reduced this length of channel and increased the stream gradient (Figure 8.1). It is difficult to establish just when these occurred and whether they were natural or artificial. However, it appears from the surficial features that they are recent (earlier twentieth century or late nineteenth century) and have initiated nickpoint retreat and channel incision (Figure 8.2). After 1942 floods have contributed to further downcutting and nickpoints have proceeded up North Arm and Missabotti Creek and these nickpoints are still progressing slowly upstream at present.

An example of declining sinuosity for an extended length of channel can be seen in upper and middle Missabotti Creek in Figure 8.1. In 1942 more than 9 km of valley length supported 12 km of channel with a sinuosity of 1.31. By 1991 the same length of valley contained a much wider stream reduced to 11.25 km in length and with a sinuosity of 1.23. These changes represent a 6.5% increase in gradient. At locations along this reach where individual bends have cut off, the change in sinuosity is clearly much more substantial and gradients have increased locally by 200-300%. Further examples of channel cut-offs can be seen in Figure 8.3. Two meander bends present on Missabotti Creek at the Kennaicle Creek junction (Sites M2 and M3) in 1942 having been completely cut-off by 1991. This reduces the channel length at this point and therefore increases stream gradients accordingly.

Figure 8.4 shows narrow and deep channels on North Arm and Buckra Bendinni Creek in 1942 (Sites N3 and B2). By 1991 both streams had undergone substantial widening and shortening with the pools in Buckra Bendinni Creek infilling across this period. Figure 8.5 shows that channel expansion has been pronounced since 1942 in North Arm and Missabotti Creek (N5 and below M4), with large deposits of unconsolidated gravel readily apparent by 1991.

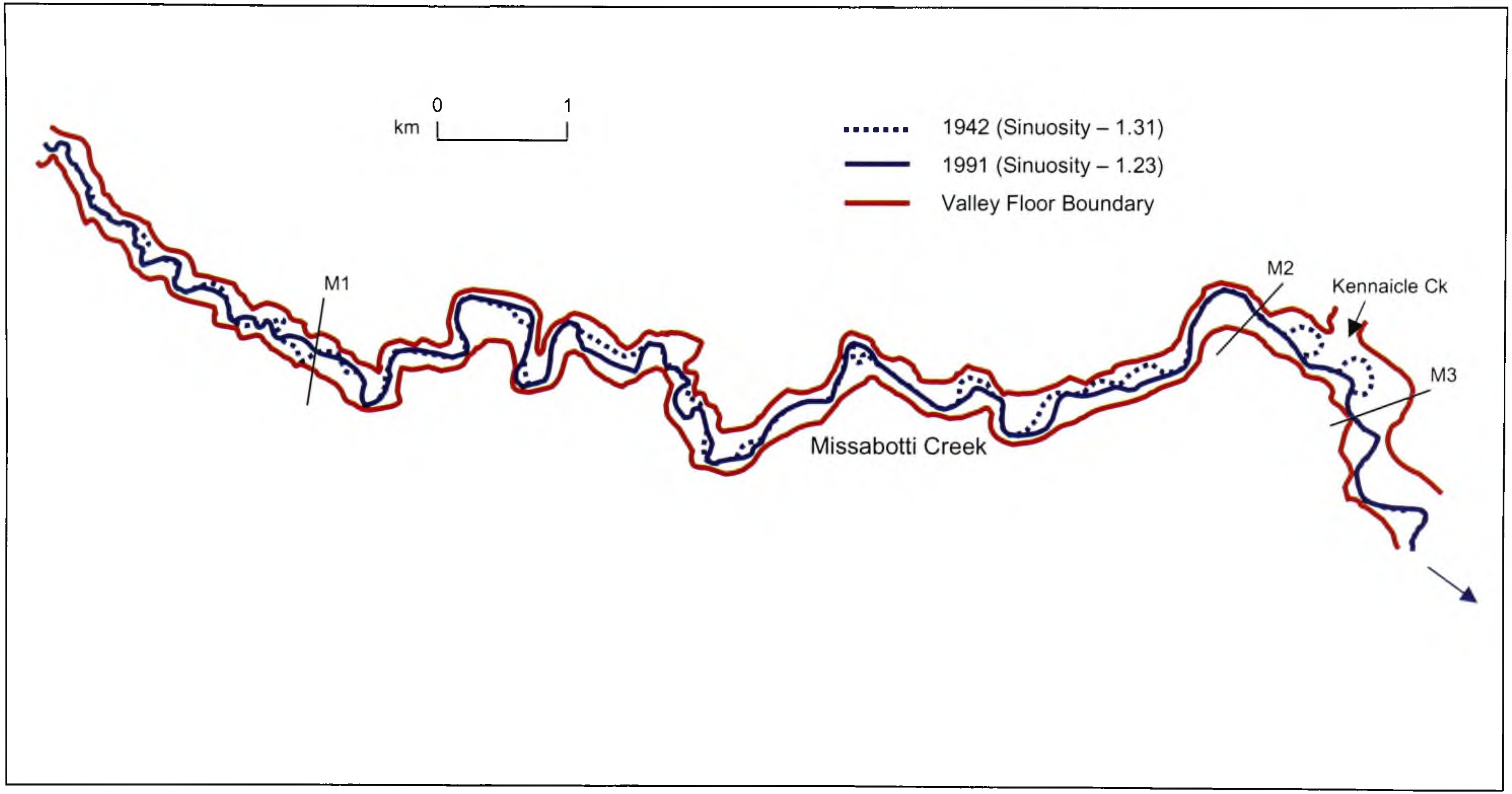


Figure 8.1: Channel change on Missabotti Creek 1942-1991

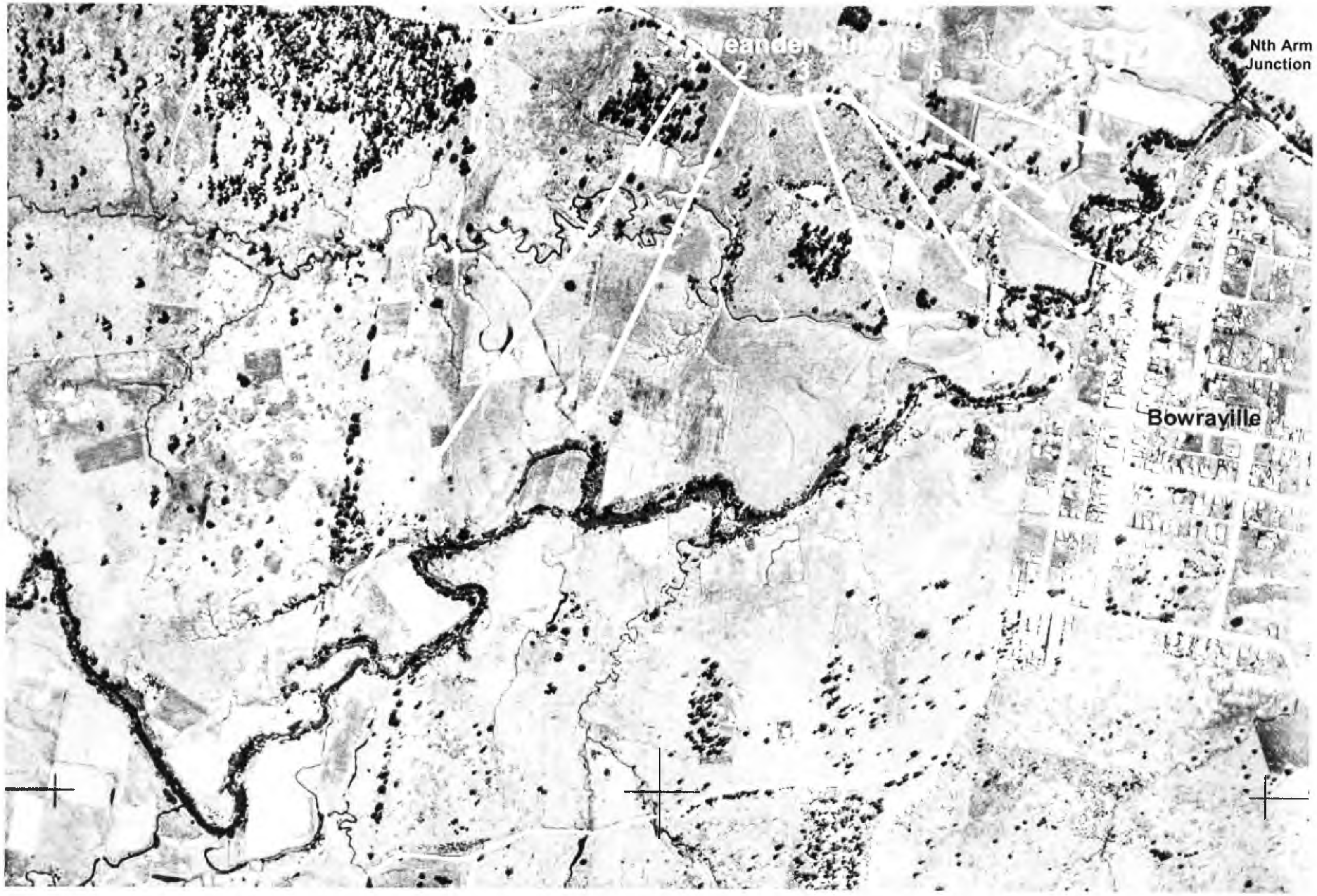


Figure 8.2: Meander cut-offs evident on lower South Arm in 1942

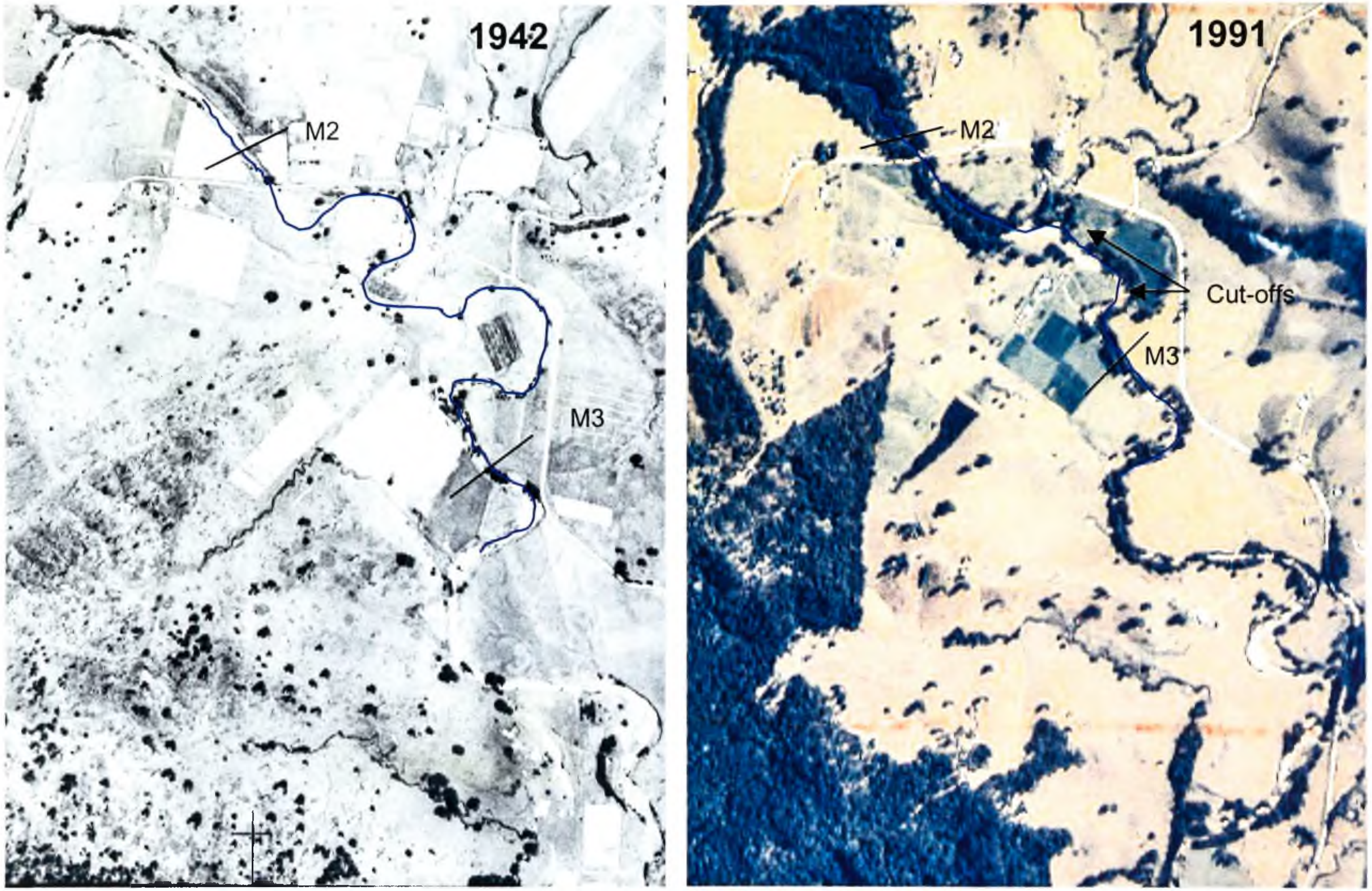


Figure 8.3: Meander cut-offs between 1942 and 1991 on Missabotti Creek

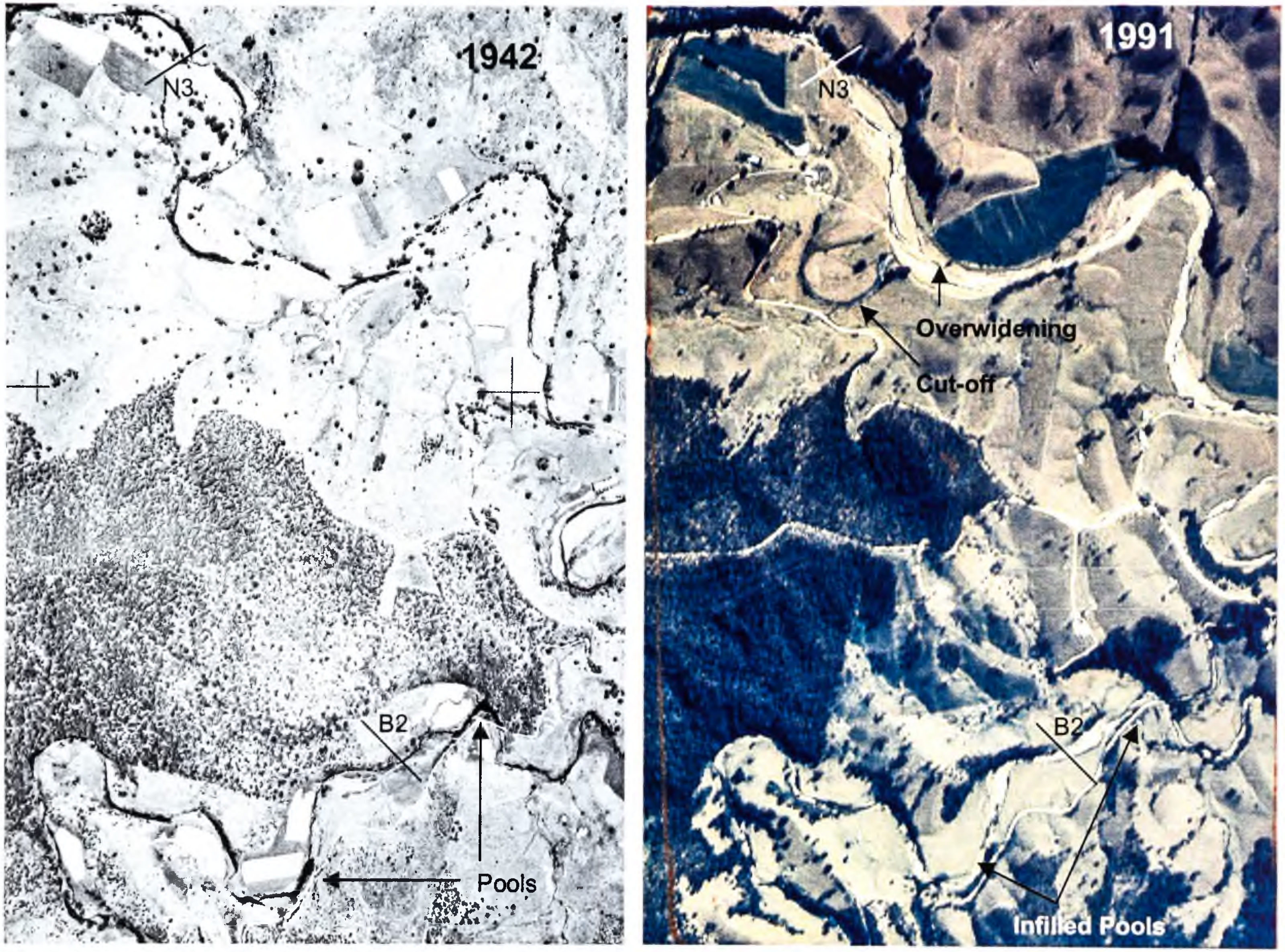


Figure 8.4: Aerial photograph comparison 1942-1991: North Arm Site 3 and Buckra Bendinni Creek Site 2

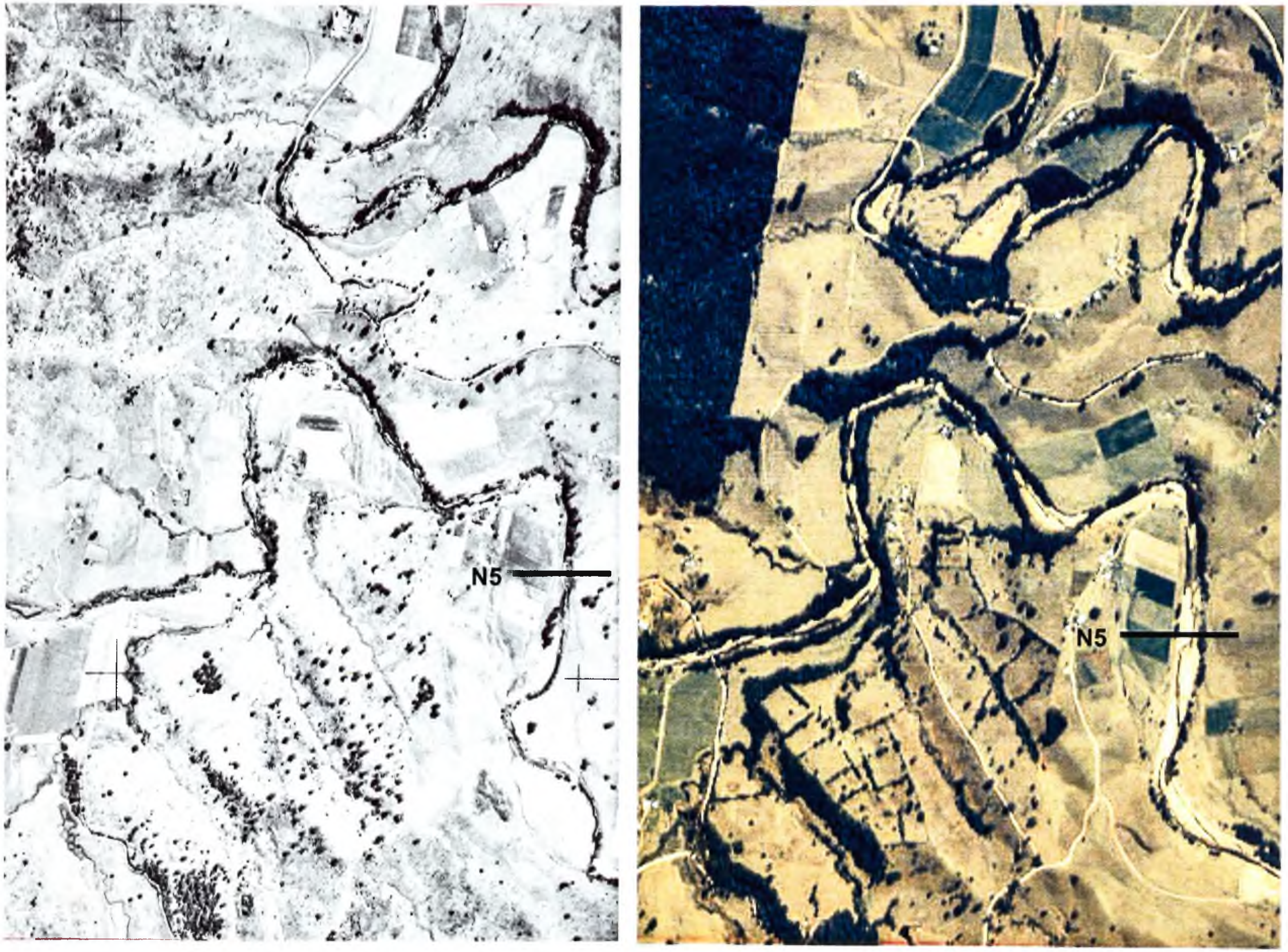


Figure 8.5: Aerial photograph comparison 1942-1991: Stream widening around North Arm Site 5

8.1.2 The Role of Vegetation in Bed Degradation and Channel Expansion

An analysis of the role of vegetation in the Nambucca is given in Chapter 5. Below is a review of the issues associated with vegetation and the role of vegetation in current catchment processes.

Channel expansion and the collapse of riparian vegetation into the channel commonly occurs following bed degradation. Under these conditions, large trees collapsing with the banks may *appear* to be causing bank erosion. This is a process currently occurring along lower North Arm about 300 m upstream of N7, where camphor laurels are falling into the channel, and at D3 on Deep Creek (Figure 8.6). However, in most cases bank erosion has almost certainly proceeded irrespective of whether this vegetation was present or not. Indeed, for areas where vegetative cover is of sufficient density (and where the incision is not too deep), the overall rate of bank erosion will probably be slowed by the presence of the vegetation. An example of this situation is given by Cohen (1997) for Jones Creek in East Gippsland, Victoria, where a fully forested system is experiencing similar channel instability to that in the Nambucca catchment. In Jones Creek the instability is associated with bed lowering on the Genoa River, into which Jones Creek flows. This study has illustrated that even the largest trees can be undercut and collapse into the channel once incision extends in depth below the root zone.

Figure 8.6: Exposed banks and tree collapse at the lower ends of North Arm (left) and Deep Creek (right)

Island formation in channels is sometimes caused by vegetation establishing on bars within the channel, and in some cases these can grow and defect the flow on to adjacent

banks. This has occurred between Sites N4 and N5 on North Arm, in the upper reaches of Taylors Arm and, at a number of locations on Missabotti Creek above the Kennaicle Creek junction.

Riparian vegetation removed following European settlement has altered the dominant bank erosion process from relatively minor corrasion to one dominated by mass failure as the channel incises and the banks increase in height. Increases in stream power and bed-load transport are associated with channel expansion from banks dominated by mass failure. Options for using vegetation as a management tool are greatly diminished compared to the situation before bed degradation occurred.

The mismanagement of riparian vegetation in the Nambucca catchment is highlighted by the desnagging program implemented under the 'Red Scheme' in the early 1970's. The sites that were designated to be desnagged were outline by the Water Conservation and Irrigation Commission (1970). These works included clearing, desnagging and lopping along 62 km of Taylors Arm, 40 km of North Arm, 8 km of Missabotti Creek, 21 km of South Arm and 20 km of Buckra Bendinni Creek, although not all of these sites were completed in full. Whilst desnagging may decrease localised channel erosion from flow deflection around fallen timber and tree stumps, it will greatly decrease roughness and increase flow velocities, thus reducing bank resistance to erosion. For example, if Manning's n at Site W2 decreased from 0.09 (a site extremely well vegetated with a lot of LWD and within-channel vegetation at present) to a much less rough 0.05 (a value recorded for most of the other sites in this study), bankfull discharge would increase from 73.5 m^3/s to 132.3m^3/s, giving an 80% increase in mean velocity. It is difficult to assess the impact of the 'Red Scheme' desnagging program, as records were not kept of what *exactly* was done or what followed, but anecdotal evidence from landowners suggests that bank erosion and gravel mobilisation was a direct consequence.

8.1.3 Perched and Incising Tributaries

As illustrated in the Jones Creek catchment in East Gippsland by Cohen (1997), tributaries can erode dramatically in response to bed lowering on the main channel. From an examination of tributary gullies on aerial photographs of the Nambucca catchment, it is possible to detect bed lowering on the main channels. On the aerial photographs gullies have become incised by 1991. On Missabotti Creek this is noticeable due to excessive

channel and gully expansion immediately above confluence with the main channel. Kennaicle Creek shows a sharp steepening of its gradient where it enters Missabotti Creek, and there is evidence that the bed of the former is also lowering. Other examples of perched and incising tributaries occur on Buckra Bendinni Creek and South Arm (downstream of S3; Figure 8.7). In the latter case, this renewed activity has caused a meander cut-off on the main tributary.

Figure 8.7: Severe nickpoint retreat on tributaries of the Nambucca catchment

8.1.4 Bank Erosion

Bank erosion is closely related to the height and angle of the stream bank, and the shear stresses applied to the bank material. In stable banks (including the toe of the bank) the cohesion of the soil and angle of the bank are commonly perceived as the most important parameters to consider (eg. Thorne and Osman, 1988; Osman and Thorne, 1988). The emphasis on the importance of vegetation, along with cohesion and angle, is referred to by Millar and Quick (1996) and by Hupp and Osterkamp (1996). Shear stress values shown in section 4.5.5 show the relative strengths of material in different

reaches of the Nambucca catchment. Even where gravel is eroded from the toe of the bank, continued mass failure is dependent on the shear stress required to fluvially entrain and remove basal units of slumped debris (Osman and Thorne, 1988).

The composite river banks in the Nambucca catchment are made up of cohesionless sand and gravel overlain by cohesive silts. The erosion of the gravel leaves a block or cantilever of stable material above. Cracks due to stress release, desiccation and tension can develop rapidly between block and bank (Thorne and Tovey, 1981). Failed blocks may lie at the base of the bank and partially protect the toe (Figure 8.8), or they may break apart upon falling, making for easy removal from the toe by fluvial entrainment. The blocks may roll or slide, or disaggregate as a result of water saturation. Their removal completes the cycle of erosion of the composite bank, which will then proceed to undercut again. The balance between rates of sediment supply and removal from the toe controls the banks profile and rate of retreat. As this balance depends on fluvial processes, the profile and retreat rate are fluvially controlled even though the dominant failure mechanism of the upper bank is not directly fluvial in nature (Thorne, 1981).

Bank erosion analysis on the Bellinger River by Warner and Paterson (1987) indicates that 30 ha of alluvial land has been lost downstream of Bellingen and in the lower Kalang Valley between 1942 and 1983. Bank erosion in the Nambucca catchment itself is a secondary process following channel incision. It is likely from observations along rivers such as the Thurra in Victoria, which prior to channel incision and removal of LWD and bank and floodplain vegetation, the above mentioned bank-erosion process rarely operated in the Nambucca catchment.

Figure 8.8: Bank slumping (M1 – left) and bank collapse (T5 – right) in the Nambucca catchment

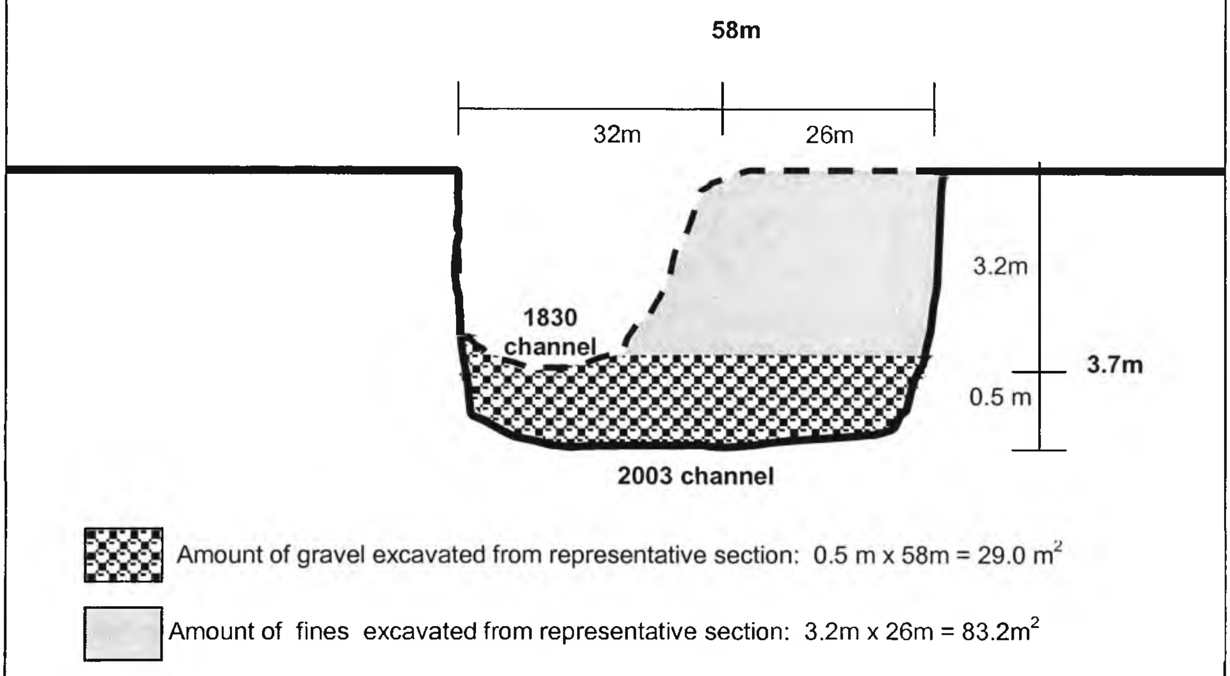
8.1.5 Estimated Channel Expansion and Sediment Erosion

In an attempt to estimate the amount of floodplain material lost as a result of channel enlargement, stable channel widths were estimated using the equation $W = 4.54Q^{0.33}$ (where W = bankfull width, and Q = bankfull discharge HEC-RAS) derived empirically by Richards (1976) for obtaining the maximum stable width of gravel-bed channels in the United Kingdom. Assuming the Nambucca streams were in some form of equilibrium with their gravel load the equation was used to provide possible widths (Table 4.9). Of course, bank material and bank vegetation play an important part in controlling channel width, and it is very likely the pre-European channels of the Nambucca were narrower than an average gravel-bed river in the UK due to the dense rainforest and wet sclerophyll cover (Brooks, 1999). However, this equation provides an estimate of the *maximum* likely widths that prevailed in the Nambucca at the time of settlement. The *minimum* volume of sediment that has been eroded from the banks can be calculated and North Arm is used as an illustration of this approach.

Using the equation above, and from discharges calculated in Table 4.9, the theoretical mean stable bankfull width for the seven sites on North Arm was 32m, a figure that was used in assuming pre-settlement mean channel width. Taken from cross-sections, the actual mean bankfull width on North Arm was calculated to be 58m, with a mean depth of 3.7m. To estimate mean bed lowering on North Arm, field observations and comparative cross sections (Appendix 9) were used. A conservative estimate of 0.5 m of bed degradation was then assumed to have occurred on North Arm since settlement. From

this, it can be estimated that the average channel dimensions at bankfull stage were 32m in width and 3.2m in depth.

Assuming that the gravel layer was not above bed level pre-settlement, it was estimated that 0.5 m of incision and 26m of overwidening on North Arm would have eroded 29m3 of gravel per metre of channel length and 83.2m3 of overbank fines per metre of channel (Figure 8.9). Over the 55 km of channel on North Arm this equates to 1,595,000 m^3 of gravel and 4,576,000 m^3 of overbank fines have been eroded from North Arm. These figures are not intended as precise measurements but are a guide to indicate the broad magnitude of sediment reworking in these streams since European settlement. Given that these estimates are conservative the actual figure could well be far greater.



Estimate of gravel released into North Arm System: 29.0 m^2 x 55 km = 1,595,000 m^3
Estimate of fines released into North Arm System: 83.2m^2 x 55 km = 4,576,000 m^3

Figure 8.9: Estimates of material eroded from North Arm since settlement

8.1.6 Changes in the Proportion of Valley-Side Support

In the confined valleys of the Nambucca 1942 aerial photographs indicate a tendency for undisturbed streams to run in long pools against a valley side (consisting of bedrock or indurated alluvium) and then travel sinuously to the other side of the valley. As a result a significant proportion of total stream length is supported by bedrock or by a bank of indurated alluvium (eg. terrace). It was then observed that, by 1991, some of the worst bank erosion and channel expansion has occurred in instances where channels flow in a near-straight line from valley side to valley side. With the reduction in sinuosity described above, the channel tends to take a relatively straight path across the valley before impacting abruptly against the opposing valley side. In places where the stream flows in an almost straight line from one valley side to the other, the steeper gradient makes these reaches scour and become prone to erosional instability. The impact of flow against the side of the valley at the end of such a straight alluvial reach can produce considerable turbulence which deflects flow across the channel, eroding the alluvial convex bank of the bend and the alluvial bank of the adjacent pool (Figure 8.10). Eroded material is then deposited, causing widening and shallowing of what was previously a long, deep and narrow pool.

Channel migration and an overall steepening of the stream gradient have, in some reaches, resulted in a total reduction of the length of stream supported against the valley sides. What this means is that the overall shortening of stream length has moved the stream away from a non-erodible boundary, thereby depriving the channel of stable locations to form pools and to dissipate surplus energy. This is illustrated by an examination of 2.2 km of river valley in upper North Arm (Figure 8.11). Between 1942 and 1991 there was a 5% reduction in stream length and this reduction in sinuosity led to a 12% or 140 m reduction in the length of stream in direct contact with the valley sides. In addition to the effect on energy dissipation, these findings have important ecological implications in relation to the loss of pool habitats.

Figure 8.10: Overwidened pools in bedrock valley side areas on Taylors Arm (left) and Buckra Bendinni Creek (right)

8.1.7 Cattle Trampling

An important but little discussed factor in most rural catchments is the effect of cattle trampling and grazing on fluvial erosion. Trimble (1994) found that grazed stream banks in Tennessee, USA, eroded three to six times faster than ungrazed reaches. Most of the damage results from cattle accessing the creek and the breaking down of banks with their hooves as they do so. Apart from causing bank erosion, cattle can inhibit stream rehabilitation. By grazing within the channel boundary cattle interfere with vegetative regrowth and reduce flow roughness and sedimentation on the banks, bed and bars of the channel. An example of the difference that cattle exclusion from stream banks can make to vegetation growth along a channel is shown for Buffalo Brook in Tasmania in Figure 8.12. Once the bank is protected, vegetation will re-establish on both the concave and convex banks.

Further damage attributed to cattle activity is the disturbance of the bed armour. Jain and Park (1989) indicate the importance of bed armour in stabilising disturbed reaches. However, access to the stream by cattle can cause trampling of the bed and banks (Figure 8.13), pushing smaller bedload particles to the bed surface and thereby increasing the chance of enhanced bedload entrainment.

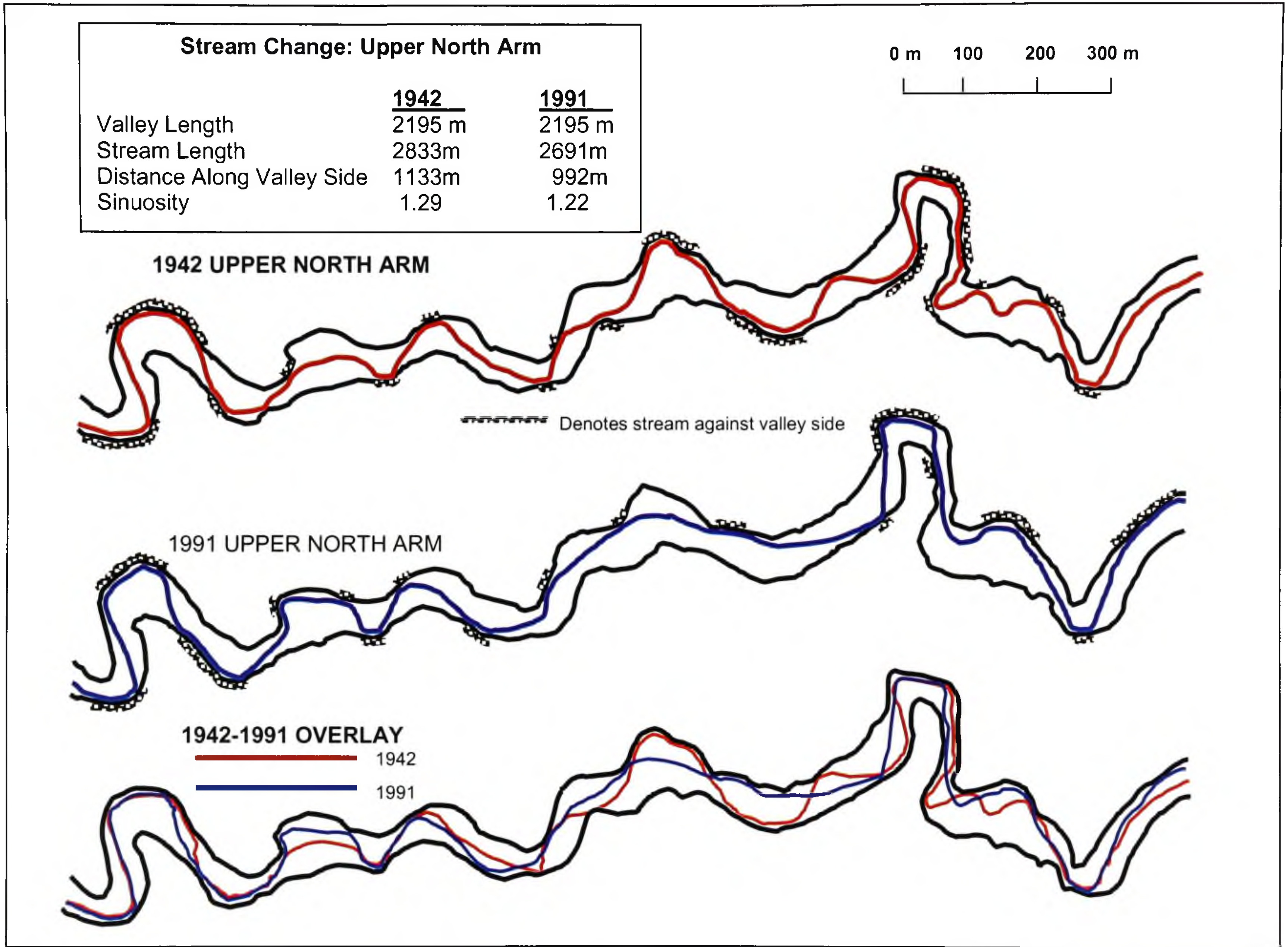


Figure 8.11: Evidence for streams moving away from valley side confinement from 1942-1991 on Upper North Arm

Figure 8.12: Recovery of Buffalo Brook in Tasmania after cattle exclusion for 10 years (1986-1996) (Photos: Lindsay Nicholson)

Figure 8.13: Cattle trampling at a stock access point at North Arm Site 2

8.2 Stream Management in the Nambucca Catchment

8.2.1 Flood Mitigation

Prior to the late 1960's there is little documented evidence of river management practices in the Nambucca catchment. Major forms of stream management were not official practice although there were efforts at erosion control and flood mitigation by individual landholders. Anecdotal evidence obtained from a questionnaire circulated by this study to residents (Appendix 2) indicates that Nambucca Shire Council removed gravel from within the channel of North Arm as early as 1928. Information from the questionnaire also indicated that after the 1950 floods there were very large amounts of gravel removed from newly formed point bars. Apart from gravel extraction (see chapter 2), desnagging and the excavation of meander cut-offs have been practiced by landholders as recently as the 1990's.

Documented evidence of government led stream management began with a NSW Water Conservation and Irrigation Commission (WC&IC) document in 1970. The document, entitled "River Improvement Works within Nambucca Shire", examined Taylors Arm, North Arm, South Arm, Buckra Bendinni Creek, Missabotti Creek and Kennaicle Creek. Along lengths of each stream, river improvement engineers outlined the work required and estimated the cost for these works. The river works included; channel clearing and desnagging, tree lopping, channel realignment, bank protection, wire meshing for bank protection, earthworks and willow planting. The overall objective was to clear the channel of the debris that was slowing floodwaters and, to provide bank protection in reaches where bank retreat was becoming a concern.

A summary by the senior improvement engineer sets the scene in terms of the economic and social cost of river erosion at the time (WC&IC, 1970 p.1):

> "Over a period of many years most of the creeks and streams in the Nambucca River Valley upstream of the township of Bowraville have suffered damage from floods. Riverbank erosion and movement of the channels have been the biggest problems to landholders. Generally, river flats in the Nambucca River Valley Catchment are scarce. Where they do exist, they are fertile and quite valuable. The

> erosion which has gone on unchecked in the past has made large inroads into these flats and in a lot of cases, particularly in the upper reaches of the various tributaries of the Nambucca River, landholders have been forced to leave their properties and move to towns and cities to find other employment for their livelihood."

Looking at the condition of the stream and the cause and remedy of the flooding problem, he continues (WC&IC, 1970 p.1):

> "Conditions in each stream vary from poor to very bad, the two worst streams being North Creek and Missabotti Creek where river bank erosion is very bad. In all streams obstructions to flow are a major problem. Most channels are blocked by dense vegetation growth and other debris. In some places gravel has built up against tree growth and as a result flows have been diverted, at sharp angles, causing poor alignments to develop. Much of the flooding of flat land could be attributed to these conditions."

These interpretations appear to have been reached in ignorance of the fundamental cause of stream degradation in the Nambucca catchment; that of vegetation clearance and consequent riverbank destabilisation.

Cost estimates in 1970 for flood mitigation and bank protection works on each stream were as follows (WC&IC, 1970):

Taylors Arm	$193,070
North Arm	$400,840
South Arm	$ 46,125
Buckra Bendinni Ck	$ 34,965
Missabotti Ck	$ 78,425

The total cost estimated for the catchment as a whole was $753,425 which is equal to Aus$6,027,400 in 2001 terms (Reserve Bank of Australia, pers. comm., 21/3/2002)

Flood mitigation studies of the tidal reaches were also carried out by the Department of Public Works (1974). In 1979 the Water Resources Commission repeated the work of the

WC&IC (1970) by identifying eroded sites and estimating the repair costs for the non-tidal channels of the Nambucca. The methods of river improvement included stream clearance (classed as light, medium and heavy), mesh bank protection, rock-fill bank protection and willow planting.

Cost estimates in 1979 for each stream were as follows (Water Resources Commission, 1979):

Taylors Arm	$342,000
North Arm	$915,000
South Arm	$704,000
Buckra Bendinni Ck	$193,000
Missabotti Ck	$578,000

The estimated cost for the river improvement works in the catchment totalled $2,232,000 which is equal to Aus$8,258,400 in 2001 terms (Reserve Bank of Australia, pers. comm., 21/3/2002)

The enormous cost estimated to carry out stream management practices throughout the 1970's should not be lost on stream managers today; however, the management rationale today is different. The aim in the 1970's (and into the 1980's - see Gutteridge et al., 1981) was to decrease the height of floodwaters by clearing the channel and allowing greater velocities. The approach at the time was best put forward by the principal engineer of the Water Resources Commission (Rankin, 1980 p. 132):

> "When the flow is blocked by a badly obstructed channel the discharge is not reduced...one of the most obvious benefits of stream clearance is that the removal of obstructions will increase the actual waterway capacity of a congested channel. The discharge in the stream will not be altered. The overall rate of flood flows will not be significantly increased and there will be less turbulence."

This statement is clearly incorrect. The water discharge in the stream channel will certainly increase following stream clearance, as less water will flow over the floodplain.

Studies at that time, and subsequently, have proven the very considerable value of vegetation and large woody debris in maintaining bed and bank stability (eg. Keller and Swanson, 1979; Smith et al., 1993; Assani and Petit, 1995). Today it is recognised that vegetation above low flow is very important for bank protection and overall channel stability. LWD plays an important role in bed stability and works best in conjunction with an established riparian vegetation zone. By stabilising the bed and reducing flow velocities, LWD can prevent excessive bedload transport and help maintain pools and riffles (Keller and Swanson, 1979; Assani and Petit, 1995).

8.2.2 Rivercare and Landcare

In the late 1980's a nationwide change took place in the approach to land management. At a national level, funding became available for Landcare - a national strategy of community based conservation strategies aimed at preventing further soil, water, vegetation and land degradation. At the state government level the NSW Department of Land and Water Conservation (DLWC) (formerly known as the Department of Water Resources - DWR) began to work in association with the National Landcare Program to establish and oversee Landcare groups.

In the 1990's the DLWC began a 'Riverwise' program aimed at educating local residents about their rivers. This program attempted to get locals interested in 'owning' the problem of managing their local stream and thereby becoming involved in carrying out river rehabilitation (Outhet, 1996).

In addition to the 'Riverwise' program is the 'Rivercare' process. On the mid-north coast of New South Wales the DLWC followed up an extensive period of river improvement works on the Hunter River with a community driven and community involved series of works on the Manning River. Rivercare works are now the result of DLWC consultation with Landcare groups. Enlarged aerial photographs are used as the basis for the planning with transparencies overlain to provide different types of relevant information such as known points of erosion, property boundaries and the extent and alignment of any proposed remediation works. Additional stages involve the assessment of permit

applications, discussions upon the best method of river management and formal submissions of proposals.

Since the advent of 'Rivercare' and 'Riverwise' the number of Landcare groups in the Nambucca catchment grew from two in 1991 to fourteen in 1996. Each Landcare group organises its own funding applications and working bees. Due to the number of Landcare groups in the catchment, a Landcare co-ordinator was appointed in 1995 funded by the National Landcare Program.

The Landcare groups in the Nambucca catchment (and the study sites within these group areas) include Upper Taylors Arm (eg. Site T4), Medlow (eg. Site T7), Utungun (eg. Site T10), Upper North Arm (eg. Site N2), Argent's Hill (eg. Site N3), Goalloma (eg. Site N4), North Arm/Missabotti (eg. Site N6), Junction (eg. Site N7), Nambucca River (downstream of N7), Upper Missabotti (eg. Site M1), Sullivans Missabotti (eg. Site M2), South Arm (eg. Site S3), Buckra Bendinni (eg. Site B3) and Valla (eg. Site D3).

In most cases the bulk of the funding required was for earthmoving machinery for tree felling, log or rock placement, or the removal or relocation of soil and gravel. Local contractors carried out these tasks. *Jobskill* teams funded by the federal department of employment, education and training carried out further work involving weed control and tree planting, stock fencing, and groyne and jack construction.

As the era of Landcare arrived, with it came a new focus involving specific investigative studies in the Nambucca. The emphasis on flood mitigation, which prevailed throughout the 1970's and early 1980's, was no longer evident. The new emphasis was aimed at controlling bank erosion and managing gravel deposition. Apart from several DLWC papers there were reports published by consultants (eg. Resource Planning, 1989; Thoms, 1994) examining bank erosion and the role of gravel extraction. DLWC produced papers on the importance of riparian vegetation (Raine, 1994) and provided guides for the implementation of river works that were required throughout the catchment (DLWC, 1995). All of the reports cited above called for a major scientific study to examine the cause of degradation and identify the steps involved in remedying the problem. This major study was the basis of this thesis.

8.3 Approved Rehabilitation Methods Used in the Nambucca Catchment

The main methods of stream rehabilitation in the Nambucca catchment carried out under the auspices of Rivercare and Landcare are:

- Log sills
- Groynes (pin groynes and brush groynes)
- Jacks
- Rock ramps
- Bank and toe revegetation

The following sections provide a summary of each method including selected examples and the perceived advantages and disadvantages of each method.

8.3.1 Log Sills

Log sills are used in an attempt to restore the natural pool and rifle sequence that refers to quasi-regular alterations of shallows and deeps that are characteristic of gravel-bed channels of moderate slope. Pools and riffles are marked by stage dependant contrasts in flow velocity, water surface slope, channel morphology and bed sedimentology. Over most flow ranges riffles are shallower, faster zones of steeper water-surface slopes, with coarser, better-sorted or more interlocking bed material than intervening pools (Clifford, 1992). Thompson et al. (1996) have concluded their research on sediment transport in pools and riffles by stating that pools are more competent zones of bedload transport than are riffles during high flows.

Local scour of a single pool creates deposition downstream which then generates the next downstream flow irregularity (Clifford, 1992). In general terms pools are most commonly found on the outside of bends with riffles found in the intervening straight reaches. In instances where a channel has undergone bed and bank erosion, a priority with river managers is often to reconstruct the pool and riffle sequence. It has been recognised that the protection of an outer bank in a meander bend could be in ignorance of bed lowering which may be the real cause of channel instability at a given location

(Neill and Hey, 1982). In streams that are actively eroding, the channel slope is increased by reducing the sinuosity. In these circumstances it is sensible to decrease the gradient in the meander bend by introducing small scale drop structures on the riffles between bends, reducing average flow velocities in the upstream bend and lowering outer bend shear stresses (Neill and Hey, 1982). This is the theory behind the use of log sills.

Log sills are the most widely used form of bed level control within the catchment. At a cost of approximately $1500 each they were identified as a cost-effective method to restore the pool and riffle sequence to degraded channels in the Nambucca catchment. The concept of a log sill is simple; partly submerged logs roughly transverse to flow are used to dissipate energy and help control the transport of bed material downstream. Logs are usually large hardwood trunks that exhibit longevity in water. There have been two types of log sills trialled in the Nambucca with differing results; straight log sills and v-notch log sills.

The straight log sill consists of a single hardwood log (or two logs together end-to-end) perpendicular to flow (Figure 8.14). The log is covered with a permeable fabric named *geotextile*, which is buried 2 metres under the gravel on the upstream side of the log and 1.0-1.5 metres below the log on the downstream side. The *geotextile* membrane helps to raise the water table at the site and helps prevent the gravel washing out from beneath the log.

A v-notch log sill consists of two logs joined together end-to-end in a v-shape with the apex pointing upstream (Figure 8.15). This configuration causes water flowing over the sill to scour down the centre of the channel. In the Nambucca catchment, scour holes on the downstream side of the v-notch sills can be up to 1.5 metres deep at the face of the log but they diminish in depth downstream (DLWC, 1996). The straight log sills do not form scour holes as deep as the v-notch sills. In some cases rubber tyres, an additional partly buried log or rubble has been used to dissipate energy on the downstream side so as to help prevent undercutting of the sill. In some places in the Nambucca catchment log sills were placed in a downstream series of up to 10 about with a head loss of 0.2-0.3 metres for each (J. Bucinskas pers. comm.)

A major problem with log sills is that they can be outflanked by the flow. Figure 8.14 shows a straight log sill working on Taylors Arm. The success of this sill is, in part, due to the protection given by a 'splash log' placed on the downstream side of the main log, and to the placement of brush groynes along the banks at the outer ends of the log. These brush groynes help to prevent the sill being outflanked by scouring in times of flood. Continual maintenance of the sills and brush groynes by property owners greatly contributes to their success. Figure 8.14 also shows a v-notch sill on Missabotti Creek where a pool has been successfully scoured on the downstream side. This sill has not been outflanked due to the fact that the logs have been embedded into a cohesive and vegetated bank of soil in contrasts to those where the banks consist of unconsolidated gravel. The narrowness of the channel here, and the decreased chance of outflanking, have helped the sill to remain intact. A possible risk with the use of *geotextile* is that when it is not constantly submerged it can breakdown, risking undercutting of the log structure.

Figure 8.14: Versions of log sills; straight sill on Taylors Arm (left) and a v-notch log sill on Missabotti Creek(right)

8.3.1.1 Log Sill Case Study: Argent's Demonstration Site (N3)

In 1995 the DLWC Task Force decided to establish a demonstration site to trial their methods of river rehabilitation and a problem site at Argent's Hill on the North Arm was chosen. This reach was in the vicinity of a meander cut-off artificially constructed by a private gravel extraction operator in the 1980's. Gravel deposition has since completely filled in waterholes and left the water table approximately 1 metre below the gravel bed during dry periods (DLWC, 1995).

The DLWC had nine v-notch log sills installed in 1995/96. A one in one year storm event in January 1996 resulted in the failure of six of the log sills. By April of 1996 eight new log sills of various design were constructed, bringing the total number of log sills in the reach to eleven. However, a one in five-year storm event the following month (May 1996) lead to the destruction of 9 of the 11 log sills. A report by the DLWC (1996 p.4) states:

> "The May 1996 flood caused many of the works at this site to fail. The main reasons for failure were the excessively steep bed due to the meander cut-off at the site and insufficient time for the revegetation works to become established. The flows over-topped the banks and many of the bed control sills failed by outflanking... the lesson to be learnt from this is that the installation of bed control works will generally be unsuccessful until they can be tied into well vegetated banks that are proven to be stable."

Figure 8.15 shows the fate of a V-notch log sill that has been outflanked. This reach was over steepened due to a meander cut-off in the 1980's. Figure 8.15 shows a comparison of the sill just after completion in February 1996 and shortly after the May 1996 flood. The sill was placed against bedrock on the left side of the channel but was only buried under gravel on the right side. The May flood caused the structure to be undercut and outflanked on the right side of the channel. The newly created channel, with a design width of 15 m, was unable to cope with the storm event and the floodwaters outflanked the log sills, also removing the groynes that were designed to prevent this from happening.

Figure 8.15: A v-notch log sill after construction at Site N3 on North Arm in February 1996 (left) and after the May flood in 1996 (right)

8.3.1.2 Log Sills Analysis:

Most of the log sills emplaced in the Nambucca catchment have been eroded. A DLWC report in 1996 found that of 55 sills constructed between August 1995 and May 1996, only 14 were a success with a further 9 being classified as a partial success. The 40 v-notch sills had a 17% success rate and the 15 straight log sills had a 47% success rate. Since then, many more have failed. From our observations it is apparent that the overwidened and bed-lowered channels found in the Nambucca are not conducive to retaining log sills for any significant period of time. Log sills fail predominantly due to outflanking or undercutting (caused by further upstream nickpoint movement or failure of the geotextile to handle the excessive scour). The straight sills have been more successful than v-notch sills, but the straight sills however do little to scour out large pools, which is an objective of sill installation. It has been noted that during high flows there is no 'drop' evident on the downstream side of most straight sills, because the transported gravel accumulates on the downstream side and forms a 'ramp'. It is only when the high flow subsides that there is some scouring and the 'drop' returns (J. Desmond, pers. comm., 1997).

Log sills appear to be a tool suitable for arresting problems in a gravel-bed river that is beginning to erode, rather than one for restoring a severely eroded gravel-bed stream.

This is particularly true in much of the Nambucca catchment where actively eroding stream banks allow the sills to be quickly outflanked.

8.3.2 Groynes

Groynes (or dykes) extend from the bank to the river at an angle almost perpendicular to the flow. They serve the following functions (Chang, 1988): (1) training a river along a desired course, (2) creating a region of low velocity to induce siltation, (3) protecting the bank by keeping the higher velocity flows away, and, (4) contracting an overly wide river channel. Types of materials used to construct groynes include (in decreasing order of size and cost): reinforced concrete, quarried rock, excavated bed material, logs and brush.

In the Nambucca catchment logs and brush have been used in an attempt to control bank erosion where there has been excessive channel widening or lateral migration. Groynes have been successfully used by excavating gravel from the inside of the bend and relocating the gravel to make a bench on the outside of the bend on which groynes are constructed. The effect is to enhance river deposition on the outside of the bend.

In the construction of pin groynes, logs 5 metres in length are cut from local forests, or from *Casuarina cunninghamiana* stands that often colonise the channel. These logs are driven at least 4m into the new bench, with the top 0.5 to 1.0 m of the logs projecting above the bar surface. The groynes look like a row of stakes aligned almost perpendicular to flow. The rows contain up to 30 logs, with each row spaced downstream at approximately 15 m intervals. Debris is caught in these structures and velocity is decreased in their vicinity, encouraging deposition along that side of the channel.

Brush groynes involve fewer log pylons. Alternatively, metal posts called 'star pickets' can be used where logs are difficult to obtain or install. *Casuarina cunninghamiana* branches or stems are placed against the pylons such that they are almost perpendicular to the flow and are tied by wire to each pylon (Figure 8.16). The downstream spacing between each groyne is generally only 10 m compared to 15 m with the pin groynes. However, the spacing increases as the rows become longer. Brush groynes not only

slow down velocities and induce bedload deposition, they also encourage suspended sediment deposition. In both types of groyne system, the spaces between groynes are seeded or planted to encourage tree and shrub growth.

In the Nambucca catchment the groynes have been installed not exactly perpendicular to flow, but are pointed slightly (10°-15°) downstream. This is intended to deflect flow away from the bank. However, there is a view that this method can concentrate flow towards the eroded bank. The theory is that high flows topple over the face of the brush groyne, or surge through the spacings of the pin groynes, toward the bank and cause scour on the downstream side of the groyne. If aligned slightly upstream the 'overflow' should head toward the centre of the channel, much in the same manner as a v-notch log sill directs flow to the centre (I.D. Rutherfurd pers. comm.). To overcome bank scour brush groynes are also placed up against the toe of the bank, parallel to flow, to dissipate the erosive power of any flow at this point. Seedlings are also planted in this section to provide further toe protection.

8.3.2.1 Brush Groyne Case Study: Operation Sue, Upper North Arm (N2)

On this property a relatively straight reach of Upper North Arm had a low flow channel migrating into an alluvial left bank, undercutting the gravel layer at the base of the profile and causing bank collapse. Due to rapid migration of the thalweg, the right bank has experienced very little deposition, thus resulting in an overwidened channel. In this instance, a large colony of casuarinas on the right bank deflected much of the flow to the left bank and contributed to the erosion of this bank.

In October 1995 a gravel bench was constructed at the base of the left bank along the 130 m reach, with 13 brush groynes made from locally felled casuarinas (Figure 8.16). After construction, 4000 seedlings were purchased and planted in November and December of 1995. Two floods in January 1996 caused the three brush groynes at the head of the works to scour, requiring minor repairs. However, the floods deposited silt between the groynes and allowed an irrigated direct seeding trial to start. The works survived the flood of May 1996 that destroyed the brush groynes at Argent's demonstration site further downstream. Casuarinas colonising a point bar on the right bank became a problem as the point bar developed towards the centre of the channel.

The result was that the three downstream brush groynes became undercut. After a small government grant was awarded for continuation of the project, the casuarinas were felled and a continuous brush groyne (30 m long) was constructed parallel to the undercut bank. In November 1996, 230 mm of rain over 24hrs on North Arm resulted in a flash flood. The groynes held up very well, the only damage being the loss of some seedlings. During 1997 ongoing maintenance and monitoring of the works have continued. Regular mowing, fertilising and mulching has resulted in excellent growth rates with many trees on the upper bank now about 1.5 m in height. In general the site has proved an excellent example for the care and maintenance required of river works after the initial works are emplaced.

Figure 8.16: Brush groynes at 'Operation Sue' on North Arm in 1997 (left) and 1999 (right)

8.3.2.2 <u>Pin Groynes Case Study: Jacques' Property, Upper Taylors Arm (T2-T3)</u>

The situation in this reach was almost identical to the one described above. In this instance however, the eroded bank face extended 400 m downstream and the channel width was over 50 m. To remedy the problem a bench was constructed in February 1997 at the base of the eroded bank using gravel from the point bar on the right bank. Using the method described above, fifteen pin groynes, in addition to eight jacks and two brush groynes, were emplaced on the newly constructed bench (Figure 8.17).

The works survived a flood in March 1997 (approximately a 1 in 1 year event), with only minor scour occurring around the brush groynes at the head of the reach. The channel maintained its new alignment and the groynes have resulted in a small build-up of gravel and some sand and silt in the embayments between the groynes.

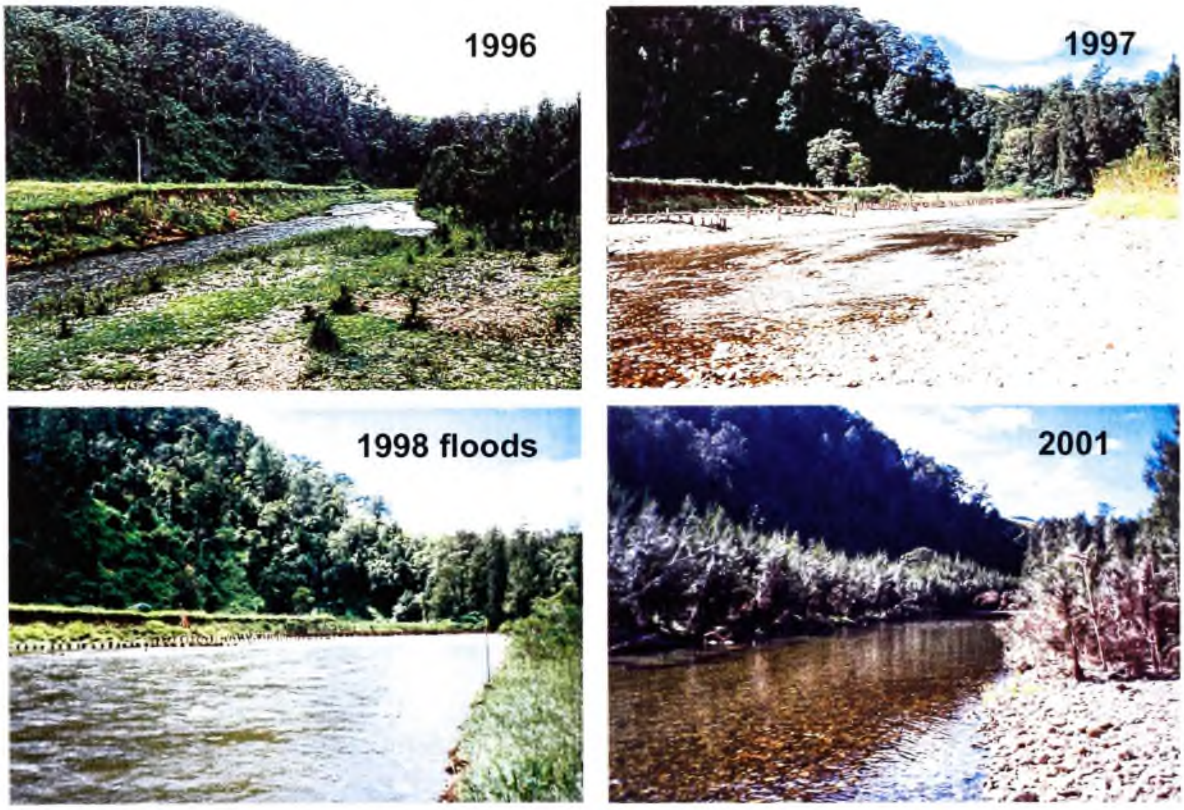


Figure 8.17: Photo record of changes associated with Jacques' pin groyne on Taylors Arm

8.3.2.3 <u>Groynes Analysis:</u>

As shown by these case studies, pin and brush groynes have been very successful in halting bank erosion along relatively straight reaches in the upper part of the catchment. Continual maintenance is crucial for the success of these structures and after each flood it is imperative that any repairs required be carried out as soon as possible so that any small problem does not become a major one.

The performance of groynes on the outside of tight bends has not been as successful, particularly in the lower parts of the catchment. An example of this is Doolan's property

(just upstream of N7). The alignment of the groynes is crucial and the use of large rocks along the toe of the bank may be necessary to help prevent flow getting in behind the groynes and causing scour. The groynes at the head of the works are, in many ways, the most important as they bear the brunt of the flow; if the flow does not get in behind these there is a much better chance of preventing bank erosion.

8.3.3 Jacks

Jacks are another form of flow retardant designed to catch debris and promote sedimentation at the base of an eroded bank. They are constructed from timber and are often placed on artificial benches made in the same manner as those that groynes are placed upon. Jacks are made by binding two pieces of wood (approximately 1.5 m long) together with wire to form an X-shape. A matching pair of "X's" is joined by a length of timber in the centre in the form of an "axle" (Figures 8.18 and 8.19). The jacks are placed perpendicular to flow and are anchored into position by wire and steel posts driven into the bench. A series of these structures are placed only a few metres apart in what is known as a 'jacks field'. This configuration allows flow to be slowed and debris to be trapped over the bench. The advantage of these jacks is that they do not fail due to undercutting or outflanking and can move to compensate for the lowering of a bench level.

8.3.3.1 Jacks Case Study: Hudson's Property, Upper Taylors Arm (Near T4)

At this site a straight reach had become overwidened due to flow being deflected from an opposing bedrock wall. A bench was constructed on the left bank by excavating some of the gravel that had filled-in the adjacent pool. An initial field of jacks was placed on the bench in late 1995. Flooding during 1996 saw sedimentation occurring in the jacks field with no further erosion occurring on the left bank. At the end of 1996, deposition had laid down silt, sand and gravel up to the cross-bar on the jacks. An additional field of jacks was constructed on top of the previous field, allowing the bench to build higher (Figure 8.18).

Figure 8.18: Jacks field at Hudson's property on Taylors Arm near Site T4

Figure 8.19: Jacks field on Deep Creek (near Site D3) in 1997 and 1999

8.3.3.2 <u>Jacks Analysis</u>

Because jacks are designed to trap moving debris and not to divert the flow, they do not pose a threat of causing further bank erosion such as a failed log sill or groyne could. Floodwaters that get behind the jacks fields do not have the same erosive power as, say, flow getting behind brush groynes, because jacks do not constrict and alter the flow as much brush groynes do. Although labour intensive when constructed by local residents,

jacks are an inexpensive way of controlling bank erosion for short lengths of eroded bank (30 m). However, a field of jacks built along an extended section of eroded bank may be too labour intensive to be viable, particularly considering the close spacing between each of the jacks.

8.3.4 Rock Ramps:

Rock ramps follow the same principles as log sills. Their objective is to dissipate stream energy and to helping maintain or recreate the pool and riffle sequence. A major difference between rock ramps and log sills is that rock ramps impart a gradual fall in the stream bed height over a 30 m distance downstream, whereas log sills provide just a single low fall. To construct a rock ramp in the Nambucca catchment is relatively expensive, costing approximately $12,000. However, if correctly positioned they have a low risk of failing. Rock ramps are best used to control bed levels in laterally stable reaches (Figure 8.20). To meet with the requirements of NSW Fisheries legislation (*Fisheries Management Act 1994*) a 1:20 slope is required (Figure 8.21).

Figure 8.20: Rock ramp on Deep Creek (D3)

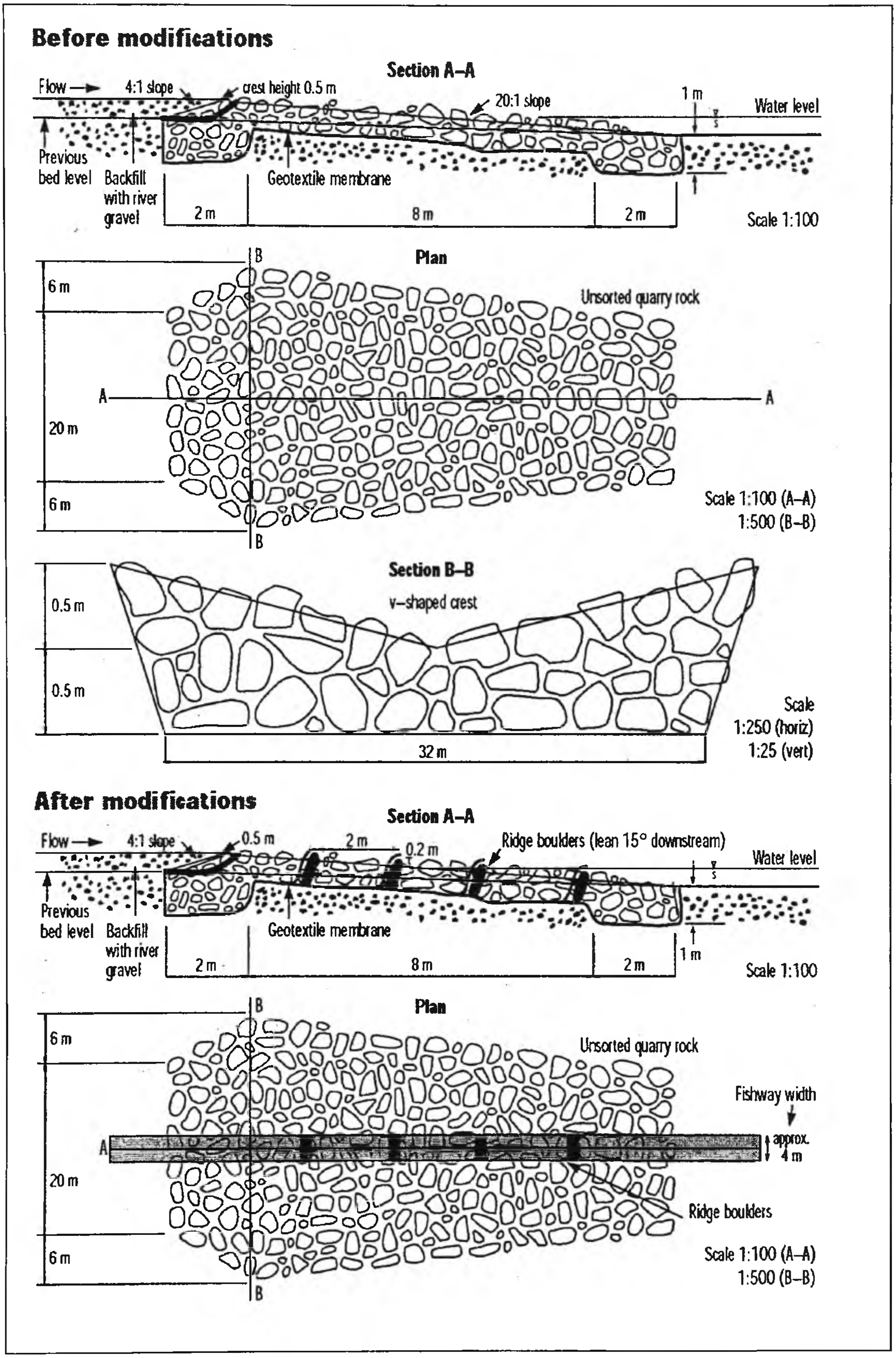


Figure 8.21: Details of a rock ramp altered to promote fish passage at D3

8.3.4.1 Case Study: Argent's Site, North Arm

A rock ramp was constructed at Argent's demonstration site in March 1996. It extends over a 30 m reach on the downstream side of a long pool that lies adjacent to a natural bedrock valley side largely clear of vegetation. The head loss over the 30 m ramp is 0.6m, equivalent to that of 2 or 3 log sills (DLWC, 1996).

Following the flood of May 1996, which largely destroyed the other works at the Argent's demonstration site, the rock ramp remained intact and has not been significantly damaged by any subsequent floods (Figure 8.22). Following its construction, a lengthy pool has formed on the upstream side of the ramp against the bedrock valley side. It is envisaged that future channel contraction along this reach will allow flow concentration within the pool to excavate the pool further. If this does occur then the rock ramp will be able to maintain the bed level through this reach.

Figure 8.22: Rock ramp on North Arm Site N3 in 1999, three years after construction

8.3.4.2 Rock Ramp Analysis

Rock ramps are an important option for channel rehabilitation, particularly in the middle and downstream reaches of the Nambucca. Their potential for creating sufficient head loss to compensate for channel straightening, and their control of bed level, indicate that rock ramps are probably the best catchment option currently being trialled to control gradients and bed levels in the Nambucca. A batter of 20:1 on the downstream face of the ramps provides satisfactory fish ladder and adds to the natural appearance of the structure. As with all of the techniques examined so far, there is a danger that the stream can outflank the ramp. This means that these structures are better suited to controlling bed levels where the channel is laterally stable. The cost of rock ramps is a major limitation, and the cost is greater at locations where the channel is very wide. However, controlling bed levels in overwidened and laterally active reaches with a low floodplain is not a simple problem and rock ramps may be the only viable solution in some cases.

8.3.5 Bank Revegetation

The disturbance and disruption of natural riparian vegetation has been probably the most important cause of channel destabilisation in the Nambucca catchment. A detailed examination of vegetation and its role in stream management in the Nambucca has been outlined in Chapter 5. A wide and diverse riparian zone is essential, not only for the stream ecology, but also to limit or prevent bank erosion and lateral movement of the channels. This will help to ensure the stability of any bed control structures. If such structures can be outflanked by a mobile channel then they are rendered useless and considerable money is wasted.

Much of the riparian revegetation work in the Nambucca catchment has been carried out by Landcare groups and Jobskills teams. It is well understood by the Landcare groups involved with such projects that in the first few years before the new vegetation at such sites becomes well established, the vegetation and the site are highly susceptible to flood damage. It should be stressed that severe damage incurred by any project in the early years does not necessarily mean that revegetation works will *always* fail at that site. It

may be that the site was unfortunate enough to experience a series of major flows immediately after the revegetation program was initiated.

Amongst the residents of the Nambucca catchment there are conflicting views as to what strategies should be adopted with regards to vegetation. These views range from removing trees and having a straight and grass-sided channels, to a fully-fenced 60 m wide tree and shrub dominated riparian zone with the channel left to find its own course within this zone.

It must be said that from a geomorphic perspective revegetation and the management of riparian vegetation are the most important aspects of river rehabilitation facing the Nambucca catchment. It is not just the initial planting that is important but also the maintenance in the form of watering, weeding and thinning of vegetation that must be done on a regular basis if such schemes are to have any chance of success. A crucial factor is the management of existing or naturally-seeded vegetation, particularly the management of casuarina regrowth. Perseverance and motivation after flood damage in order to work towards a species rich riparian zone must be very high on the list of priorities.

The development of vegetation at the toe of a stabilised bank is very important to build on the success of sills, jacks and groynes for preventing bank erosion. The management of casuarinas involves thinning dense stands of saplings, managing the height of such stands, and the promotion of other species that will eventually replace the casuarinas. As a species they play a very important role in colonising and stabilising channel banks and bars, but they need to be managed. The older trees will often need to be removed because when they fall they can tear down otherwise stable banks, and once in the channel their trunks and root systems can deflect flow into otherwise stable sections of bank.

8.4 Non-Approved Rehabilitation Methods Used in the Nambucca Catchment

Apart from the approaches mentioned above, a number of other methods of stream management have been employed in the Nambucca catchment to lessen the threat of outside bank erosion. These include channel realignment, the construction of tyre walls, the construction of rock walls, and gravel extraction from bars.

8.4.1 Realignment

Channel realignment involves the relocation of the channel and is often intended to move it away from an eroding outside bend. In the Nambucca individual landholders, often using Landcare grants, have carried out this process. A danger with realignment is that the channel is made shorter and steeper in the vicinity of a meander, reversing the natural process of lengthening, or retaining length, in the channel. Shortening the channel often results in bed lowering and increased deposition downstream. An additional problem is that realignment creates newly exposed and unprotected alluvial sections that are extremely vulnerable to erosion before vegetation has had a chance to establish. Two different examples of realignment are described here.

The first example (Figure 8.23) shows an area on North Arm (upstream of N4) where a landholder's attempt to realign the channel away from the bank has resulted in erosion within a large meander bend. The intended new channel was not only much shorter than the original channel, and therefore much steeper, but no new vegetation was established and no other attempt was made to encourage bank stabilisation. Furthermore, the project did not include the relocation of the extracted gravel to fill the old channel; the gravel was extracted for sale. The project was undertaken without permission from DLWC and was halted at the time the photographs were taken.

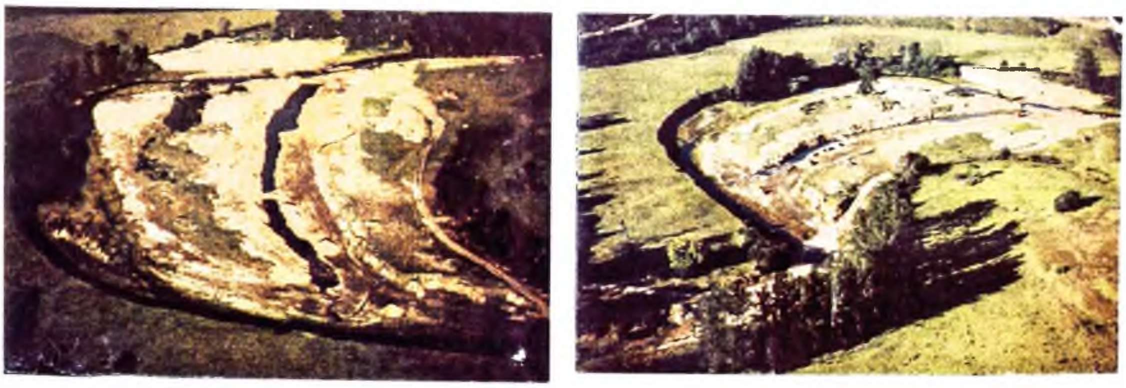


Figure 8.23: Landholder attempts at realignment on North Arm in 1996

The second example is from a reach on lower Missabotti Creek (site M4). An outside bend had been eroding into alluvial flats over a number of years prior to 1997 (Figure 8.24). A vegetation choked channel contributed to the problem. After approval was obtained by DLWC and funding arranged, the process of realignment began in April 1997. A new channel was cut through tea trees (*Leptospermum laevigatum*) growing on the channel bed, well away from the cut bank. As a consequence, the new channel had existing vegetation lining both sides, and the extracted gravel was used to fill the old channel. Soil was stripped from a high part of the adjacent floodplain-terrace to cover the gravel fill and encourage vegetation growth. Pin groynes were also placed on the fill in the old channel and extended up onto the battered lower slope of the cut bank to slow down flow that will inevitably follow the path of the old channel.

The precautions taken with the realignment work in the second of these examples by no means guarantees that this will be successful. As there were no rock ramps or other such structures to compensate for the shortened length and steeper gradient of river, future floods could disturb the bed level and undermine the gravel banks that the tea tree community is perched upon. However, this site does represent a better attempt to anticipate problems and it will be valuable to monitor its success.

Realignment, even when all the necessary precautions are taken, is a risky practice. Such projects elsewhere in Australia and overseas often require massive budgets, sometime involving concrete or rock structures to compensate for the changes in slope and width. When 'softer' engineering approaches are used, such as in the Nambucca,

there is no guarantee that the works will survive future floods over what are often substantially steeper gradients. It is recommended that future realignment works in the Nambucca also involve bed-control structures, such as rock ramps, to compensate for any associated loss in stream length and increase in gradient.

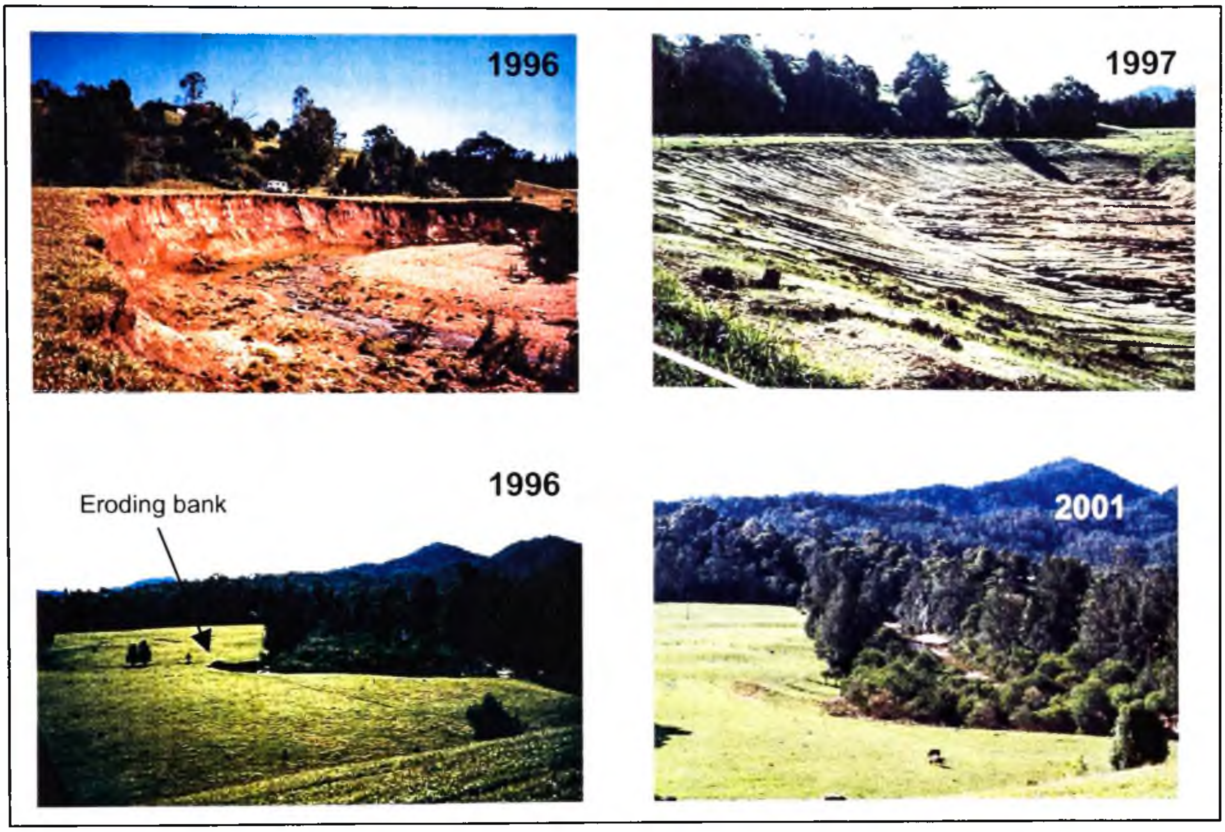


Figure 8.24: Realignment of Missabotti Creek at Site M4

8.4.2 Construction of Tyre Walls

Walls made of old pneumatic tyres are constructed to provide increased bank protection. This is a method of erosion control practised for some time in the tidal reaches of the catchment near Macksville, but has only been tried experimentally in the non-tidal reaches.

Tyre walls were trialled on a section of Missabotti Creek between study sites M2 and M3. Here, a tyre wall was constructed entirely by the landholder, without financial or

government assistance, along two 30 m lengths up- and downstream of a vehicle crossing. This reach was relatively straight but was undergoing channel expansion. The reason for this expansion appears to be due to two meander cut-offs that occurred between 1942 and 1991 between sites M2 and M3. A 0.5-1.0 m deep trench was dug along the bank face and wooden pylons were driven one metre beyond the base of the trench. Tyres were then dropped over each pylon, with the bottom two tyres placed below the low water mark in the trench. As each tyre was positioned, it was filled with gravel to weigh it down. It was then tied by wire to the tyre below. Each pylon contained 6-8 tyres with only the top 3 tyres above the ground surface. The pylon spacing allowed each column of tyres to be in contact with the next column to prevent breaching of the wall.

The tyre wall survived several small floods over a period of twelve months with only minor repairs being needed. During this time there was no further bank retreat. However, the November 1996 flood resulted in flow getting behind the wall on the upstream side of the vehicle crossing. Scour around the pylons lead to the failure of the tyre wall with the majority of tyres washing downstream. The downstream tyre wall has remained intact but requires constant repairs as flow has scoured behind the wall. After each flood gravel is bulldozed behind the wall but invariably is eroded out during the next flood.

Further to the problems experienced in this case study, there have been concerns expressed by some residents that the tyres emit harmful toxins into the water as they break down. However, this study has not examined water quality issues.

8.4.3 Construction of Rock Walls

Rock walls are used to protect the base of stream banks. Their design is simple yet expensive. Sufficiently large boulders are placed in a line at the base of an eroding bank and because these are not moved by high flows, the toe is protected from further erosion. Problems arise however if flow scours behind the rock wall. Unlike jacks or groynes, rock walls are not designed to reduce velocities near the outer bank inducing sedimentation. They are usually built to simply halt erosion rather than to rehabilitate the channel. Their

use in the Nambucca should be in conjunction with other methods of rehabilitation, rather than a solitary form of erosion control.

8.4.4 Gravel Extraction from Bars

The issue of gravel extraction is one of the most controversial issues in the catchment. Debate exists between residents themselves, and between residents and the DLWC, over the effect of gravel extraction, the supposed necessity of gravel extraction and the supposed volumes to be removed. Until the mid-1980's records of the amount of gravel extracted were so poor that estimates could not be made with any confidence. The Department of Land and Water Conservation (1995) estimated that the amount of gravel extracted from the early 1980's to 1992 from North Arm and Missabotti Creek alone was in the order of 120,000 m^3 annually, whilst the 1994 amount was in the order of 50,000 m^3. Official records collected by the Bureau of Mineral Resources from 1987-1993 indicate that an average of 95 444m^3 was extracted per annum in this period. These figures of course do not include any unofficial extraction of gravel. A survey of residents has shown that gravel extraction on North Arm and Missabotti Creek has been occurring since the end of World War 1 at least, with the periods 1970-1974 and 1989-1994 noted by many of those surveyed as periods when gravel was extracted from their properties.

A 1994 Draft Plan of Management (DLWC, 1994) endorsed gravel extraction in areas where there is no evidence of overall channel enlargement, and in these areas it was recommended that gravel be extracted only above low water flow level. Almost all of the reports on gravel extraction for the Nambucca catchment are exclusively for North Arm and Missabotti Creek (eg. Department of Water Resources, 1994; Thoms, 1994; Resource Planning, 1989). These two streams have not only the most sought after gravel type (rounded quartz) in the catchment, but they are also the most severely eroded streams. Resource Planning (1989) stated that there were over 20 sites on North Arm and Missabotti Ck that either had permits or were potential sites for gravel extraction.

The Department of Water Resources (1990) emphasised the need to endorse extraction at sustainable levels. Reviews by landholder groups pointed out the uncertainty of attempting to ascertain what sustainable levels are. Whilst sustainable yields are a

logical concept for clearly renewable resources such as vegetation, there is confusion and uncertainty as to how a sustainable gravel yield can be determined given the very limited natural supply of bedload and the inappropriateness of using bedload equations to calculate bedload yields on many NSW coastal rivers (Hean and Nanson, 1987).

Gravel extraction from point bars was seen as a means of reducing the size of the point bar and thereby reducing the deflection of flow to the outside cut bank in the bend. As a consequence there remains overwhelming support by local residents for the continual removal of gravel from point bars within the catchment. However, because of DLWC policy, the practice of completely extracting point-bars and selling the gravel has been stopped in recent years. Nowadays there is a trend to relocate the gravel from the point bar to form a bench at the toe of the eroding bank; jacks and groynes are commonly placed at the base of the eroding bank on top of this bench. Now gravel is extracted from point bars in a small number of cases where there is concern about pools infilling as a result of further point bar accretion.

The decision to place a moratorium on gravel extraction has upset many residents. They are concerned the system has an "oversupply" of gravel because bed incision, bank erosion, and a drop in the water table gives an appearance of channels with an excessive gravel load. Almost certainly there has been a real increase in transportable gravel loads. As channel sinuosity has decreased, a shorter length of river must support the same amount of gravel in transport. Furthermore, channel straightening has involved bank erosion and the release of additional floodplain gravel into the channel.

The prevention of gravel extraction along non-tidal coastal rivers in NSW underlines the growing realisation among stream managers of its harmful effects and a lack of certainty about actual bedload replenishment rates. Evidence from Australia and overseas continues to cast serious doubt over the wisdom of gravel extraction. In the Mendocino County of California, USA, a management plan recommending extraction of 50% of the natural replenishment rate on the Garcia River was reviewed by leading scientists in the field.

> "I know of no credible evidence which demonstrates that bar skimming produces positive water quality or wildlife impacts, even in areas where logging practices lead to high sediment yields and channel aggradation. First, bar skimming homogenises the cross-section and profile of a river, leading to reduced habitat diversity which, in turn, translates to declines in overall habitat quality. Second, bar skimming often leads to increases in accumulation of fines. Third, bar skimming removes the coarse surface layer, or "pavement" of a river. By controlling erosion of the bed, the pavement tends to regulate the rate at which sediment is transported through a river. When this pavement is removed or disturbed it can lead to local increases in erosion, and downstream increases in sedimentation of both coarse and fine material." – (Mount, 1996, p.1)

In review of the same management plan, Kondolf (1996, p.1) stated:

> " The suggested harvest of 50% of the replenishment rate is in general a reasonable approach, provided the replenishment is derived from erosion in the catchment upstream. However, ... there is considerable evidence that much of the so-called replenishment in the river is derived from bank erosion in the downstream alluvial reaches. To mine gravel derived from bank erosion is robbing Peter to pay Paul, unless what appears to be accelerated bank erosion is addressed and, unless the environmental impacts of such a transfer of sediment from floodplain to channel bar are fully evaluated and mitigated."

These studies raise concern about the long-term geomorphic effects of gravel extraction, particularly if the gravel entering the system is derived from floodplain or bank erosion. Without relating extraction rates to true rates of replenishment (Nanson and Hean, 1987) the widespread and unrestricted extraction of gravel from point bars could cause serious problems of channel stability.

8.5 Observations and Recommendations on Stream Rehabilitation in the Nambucca Catchment

The contemporary channels of the Nambucca catchment are far removed in form and process from those that existed prior to European disturbance. They are clearly not in balance with the alluvial floodplains they once formed. A situation now exists where

channel erosive processes are grossly out of phase with the ability of floodplain alluvium to resist these processes. The long-term objective must be to reduce channel sizes and thereby increase the proportion of large flood discharges that are routed across the floodplains. Without converting channels at great expense into environmentally-alienated reinforced "drains" of present size or greater, it will not be possible to have both flood-free floodplains and stable channels. The process of an environmentally acceptable form of channel-size reduction will entail strengthening and stabilising stream banks and immediately-adjacent floodplains with riparian vegetation. Furthermore, bed stabilisation is essential if bank stabilisation is to be successful.

Some specific facts and observations, important for the rehabilitation of the Nambucca catchment, are outlined below.

8.5.1 Geomorphic Facts

8.5.1.1 Degradation of Streams Prior to 1950

Despite anecdotal evidence to the contrary, the streams of the Nambucca were already severely degraded prior to 1950. Bed lowering and meander cut-offs appear in the 1942 aerial photographs despite long time residents claiming that such erosion occurred in the 1950's and later. Certainly, the clustering of floods from 1949-1955 catastrophically changed the channels. However, they were already greatly enlarged and unstable.

8.5.1.2 Influx of Gravel from Bank Erosion

The majority of gravel entering the Nambucca channels is derived from the stream banks and floodplains. This is similar to the situation described by Kondolf (1996) in the Garcia River catchment in the USA. Further gravel extraction from the Nambucca catchment will cause channels to adjust by eroding more gravel from the floodplains. Channel overwidening, bed lowering and the stripping of sand and silt from the channels has left the visual impression that the streams are 'choked' with gravel. In fact, the loss of such gravels is, in part, contributing to the existing problems.

8.5.1.3 Lack of Evidence for Forestry Derived Instability

Despite concern from many residents, forestry is not a major cause of bed and bank erosion in the alluvial reaches of the Nambucca catchment. Unquestionably, forestry can increase water discharge and siltation, and reduce water quality, particularly in the smaller headwater streams, but the removal of channel and floodplain vegetation is a much more serious problem for the alluvial reaches of channel below the forested areas of the Nambucca catchment. There is no evidence that forestry practices over the past several decades have caused an oversupply of gravel in the middle and lower reaches of the catchment.

8.5.1.4 The Importance of Bed Material Size

Downstream reductions in sediment size help explain why some reaches erode more readily than others. In the upper catchment the phyllite bed material has clast sizes too large for regular transport despite steep headwater gradients. In the middle reaches, the gradient decreases but the size of the bed material undergoes an even more significant reduction (eg. T2-T3), so much so that even at a reduced slope, the rounded quartz clasts have the potential to be readily transported. In the lower reaches of the non-tidal streams, slope reduces even further, yet bed material size does not change very much from the middle reaches resulting in relatively little bedload transport in the lower reaches. Bed material transport estimations indicate that on average, relatively little sediment is being moved from one reach to another.

8.5.2 Key Problems in need of Repair

8.5.2.1 Re-building of Floodplains and Benches

The overwidened and entrenched channels are, in many instances, conveying floods entirely within-bank up to 1-in-100 year occurrences (eg. T5, N4, N5). To lessen the total discharge and erosive power within the channels, benches need to form in order to consume channel capacity and to displace floodwaters on to the floodplains. For benches to form, within channel vegetation and artificial sediment traps are required. These will result in energy dissipation and reduced velocities leading to increased sedimentation.

8.5.2.2 Decreasing Channel Widths

As the Nambucca channels have become greatly overwidened and have been formed of erodible material, attempts to reduce channel size must be undertaken in manageable stages. Examples from Argents Hill (N3) have shown that narrowing the channel from 60 m to 30 m in one attempt is unlikely to be successful. The channel width needs to be decreased progressively, particularly as there is a risk that floods can occur before the stabilisation processes is complete. Once the initial reclaimed area has undergone sedimentation, and vegetation is taking hold, further artificial reductions can take place if necessary. In some cases the progressive development of riparian vegetation may cause a gradual reduction in channel capacity without further interference.

8.5.2.3 Restore Sinuosity and Stepped Bed Profile

Due to the extent of straightening, overwidening, loss of LWD and riverbank vegetation, channel lengths have become shorter, gradients steeper, and hydraulic roughness much less. To compensate for this, either sinuosity needs to be restored or stable 'hydraulic jumps' need to be constructed. Unless one or both of these are carried out, most of the Nambucca's channels will retain too much bankfull energy, threatening all methods of rehabilitation.

8.5.2.4 Restoration of Radius of Curvature to Width Ratio

When the radius of curvature (r) (measured down the centre line of a channel) is less than twice the width (w) of the channel (i.e. $r/w < 2$), the risk of erosion of the inner or convex bank increases (Hickin and Nanson, 1974). This is evident on North Arm (eg. upstream of N2), Missabotti Creek (eg. M3) and Buckra Bendinni Creek (eg. B2). Erosion of the inner bank can have a two fold effect. It can take the pressure off an eroding outside bend but it can also result in pools becoming overwidened, especially in bedrock corners. Once pools become overwidened they commonly infill with gravel. Bends where the r/w is <2 need to be modified to enlarge their curvature or to decrease their width (or both) so as to increase their erosional stability.

8.5.3 Stream Gravel

8.5.3.1 Cessation of Commercial Gravel Extraction

Gravel extraction has become a contentious issue for the coastal rivers of NSW. The rationale has shifted from one of simply exploiting an available resource, to one of exploiting a finite resource in the name of channel rehabilitation. Now channels are so severely disturbed there is a great deal of gravel derived from adjacent floodplains and terraces clearly visible in the channel. Simple sediment budget considerations mean that it is not possible to extract gravel from the Nambucca catchment channels at anything like the past rates of extraction without causing a serious imbalance in the sediment budget. A new regime of river management must ensure that as much gravel as possible is retained within the catchment's active channels. This enables rehabilitation processes to access this resource for the reconstruction of new channels, within channel benches, and floodplains.

Exceptions to this policy of not extracting gravel from the channels should be restricted to the following situations:

(1) In bedrock corners of former deep pondage (eg. T7), where gravel is depositing and not actively eroding. At these sites gravel could be extracted under the following circumstances: (a) the alluvial bank be well vegetated, (b) jacks or groynes be constructed to narrow the pool width if required, and (c) bed control structures be emplaced up- and downstream to allow any subsequent changes in the bed level to be monitored.

(2) Circumstances where gravel from an unstable reach of channel is being transported into a relatively stable reach. Here, a sediment trap should be installed at the downstream end of the unstable reach, and this trap should be regularly emptied. An example of such a location is T7 on Taylors Arm where excessive gravel transport runs the risk of filling-in a bedrock pool and destabilising the channel downstream of this site.

(3) On specific point bars, or mid channel bars, where excessive gravel accumulation risks serious channel instability. However, at these sites gravel extraction must be

seen to be a "last resort" solution to a problem that has not been successfully solved by other less drastic measures.

(4) Where gravel is extracted from one part of the channel (say a point bar) only to be placed in another part of the same reach (say a bench being built on an adjacent cut bank).

All of the above situations must be inspected and proposals approved by a qualified geomorphologist under the authority of the DLWC.

8.5.3.2 Use of Gravel Royalties to Fund Restoration Projects

The idea of letting gravel extraction royalties pay for river rehabilitation works is good in theory but not in practice. The limitations of this proposal are: (a) the gravel being extracted is usually needed to construct benches to encourage deposition elsewhere in the reach using jacks and groynes; (b) many river rehabilitation works do not require gravel to be moved at all; (c) recent literature that suggests that gravel extraction has little or no positive effect on the long term channel morphology or ecology. Using gravel to pay for river works offers a tempting option that risks creating the next problem.

8.5.4 Methods of Rehabilitation

8.5.4.1 Location of Jacks and Groynes

From observations made throughout the catchment, it appears that jacks and groynes are not as successful in controlling erosion on the outside of tightly curving meander bends as they are in stabilising and contracting overwidened straighter reaches. Due to the nature of flow vortices on the outside of a meander bend, a gravel bench constructed on an outside bend is prone to failure. Whilst a groyne may protect the bank from erosive low-stage flow, the pattern of flow at higher stages in a meander bend may direct turbulent flow into the bank. Further experimental work needs to be done to determine the alignment and spacing of groynes in meander bends, as well as determining the most useful methods of toe protection to counteract flow vortices.

Uncertainty remains over the preferred locations of jacks and groynes. In many cases they should be used together (eg. Jacques' log sills – T2). While groynes are most

successful in long straight reaches where undercutting has caused bank retreat and channel widening, jacks are the preferred method in shorter reaches of overwidened channel, particularly on bars adjacent to pools. Due to the close spacing of jacks, a channel length of over 50 m is regarded as probably too labour demanding for this form of treatment.

8.5.4.2 Location of Log Sills

Nearly all of the log sills installed within the Nambucca catchment have failed. In overwidened channels still undergoing bed degradation, their application is not recommended. The most effective use of log sills is in controlling limited bed degradation in narrow, laterally stable channels (eg. S4, B3). If a log sill can be placed between two relatively stable banks, and the bed profile maintained, then prevention certainly is better than trying to cure the problem later. Most of the disturbed channels in the Nambucca catchment need to be made laterally stable and substantially reduced in width before log sills are installed. When such sills are used, the adjacent banks must be well secured against erosion.

8.5.4.3 Toe Protection of Banks

Toe protection is often imperative where there is undercutting and cantilever failure. However, it should not be viewed as the only solution to the problem. Vegetating the toe or using heavy rock or sandbags ('gravel bags' or rock gabions) on the toe of a bank is best used in conjunction with jacks or groynes. The jacks and groynes retard flow and allow sedimentation to occur. An important factor to be aware of is the vulnerability of the upstream end of toe protection works. If it is breached here, the chance of further bank retreat downstream, no matter how solid the toe protection, is somewhat increased.

8.5.4.4 Location of Rock Ramps

Observations in the Nambucca catchment suggest that rock ramps are the best method of introducing stable drop structures in the bed of the channel. A particularly successful example is at Argents Hill (N3). However, there was also a failure on Missabotti Creek (between M1 and M2) where a nickpoint retreated around a small rock ramp. A precautionary note is that rock ramps need to be securely protected by extending them

into the channel banks. They should have a batter of approximately 1:20 to promote fish passage and to reduce downstream scour caused by over steepening. In wide and shallow channels the cost will be greater because of the added bank protection needed to prevent outflanking. In these reaches a decision will need to be made whether channel narrowing works should be carried out before grade control structures are introduced.

8.5.4.5 Cattle Exclusion

Fencing the stream from cattle is a major recommendation for the middle and lower reaches of the Nambucca stream channels. The effect cattle have on preventing vegetation regrowth and destabilising banks is underestimated by many landholders. It is only when comparisons are made between fenced and unfenced riparian zones within the catchment that the sharp contrast can be seen. Cattle trample or eat seedlings, trample the bank face and disturb the armoured channel bed. Fencing the riparian zone is essential if riparian revegetation programs are to succeed. However, cost is a major issue. Government supported in the same way Rivercare schemes are supported, is needed in order to encourage residents to carry out such projects. In the Denmark catchment of Western Australia, landholders are given grants of $400/km to fence the riparian zone, representing approximately 50% of the actual cost (Schur, 1996). Limited water access points can be included in such a fencing program, reducing the cost of water reticulation to stock kept away from most of the channel.

8.5.4.6 Monitoring of Bed Levels

Bed lowering by nickpoint retreat and less obvious gradual incision is a critical problem in the Nambucca catchment. It is not always an obvious visual problem in the manner of bank erosion or vegetation clearance. While it can occur dramatically - overnight or over weeks - it can also occur incrementally over years. The first step in controlling bed degradation is understanding the extent of the problem. This can be done in two ways. Firstly, rock ramps or log sills can be used to retain and to monitor bed levels, particularly up- and downstream of any channel works. Retreating nickpoints or other localised bed lowering will become noticeable by undercutting of these structures. Secondly, annual surveying of cross sections and long profiles in vulnerable reaches is strongly recommended to provide details of changes in bed levels from year to year.

8.5.4.7 Methods of Setting Bed Levels

Bridge piers can be threatened by bed-level lowering. This is particularly the case where the bridge is constructed over a riffle. Due to the narrowness of bridges crossing the Nambucca catchment, there is some merit in concreting the entire cross section of the channel (eg. Burrapine Bridge at T4) and ensuring the floor is sloped adequately (with a bouldery surface). If the reinforced concrete floor is only ~0.5 m thick then subsurface flow can still take place within the gravels at low stage. If the bed level lowers it will be readily visible and any nickpoints below the bridge can be stabilised with rock. There is only a threat to fish passage if there is substantial bed lowering and this can be adjusted for with the type of nickpoint stabilisation employed.

For economic, ecological and aesthetic reasons the use of hard engineering methods is not a preferred option in the Nambucca catchment. However they must, with the use of less dramatic methods, be considered if the condition of some reaches of the Nambucca catchment fail to improve. The most likely hard engineering method required could be a series of low weirs with fish passages built in severely degraded reaches to the guidelines of the Department of Fisheries. The existing situation of channels flowing in near straight lines from valley side to valley needs to be remedied by way of grade control structures or other methods that increase sinuosity. If erosion is not decreased in these reaches, 'harder' engineering options could be a necessity.

8.5.5 Vegetation Management

8.5.5.1 Species Management

The use of native species in revegetation programs is important. In other catchments in NSW 'hybrid' willows are, in fact, proliferating and have become a menace (Chapter 5). The ability of many introduced species to dominate the riverine zone and inhibit native vegetation growth is a problem. The most suitable trees for colonisation of the riparian zone are river oaks (*Casuarina cunninghamiana*), tea tree (*Leptospermum brachyandrum*), and bottle brush (*Callistemon viminalis*). All of these species play a pioneering role in the same manner as willows. Sedges and rushes such as *Lomandra*

spp. are also effective for trapping silt and providing a good ground cover beneath the native trees mentioned above.

8.5.5.2 Management of Casuarinas

Despite common perceptions, *Casuarina cunninghamiana* can play a very useful role in stream rehabilitation. As the pioneering species they have the potential, as a monoculture, to stabilise bars and benches. Selective pruning and thinning can result in a stabilised reach that supports the establishment of later successional species. River oaks are an opportunistic species and are an indicator of change. They are usually not the cause of change. Individual large trees growing precariously on the river banks may need to be removed to prevent bank collapse and flow deflection if they fall into the channel.

8.5.5.3 Maintenance of Vegetation

It is essential that vegetation is used to reduce and prevent stream bank erosion, and to facilitate the narrowing of overly wide channels. It is the most cost effective, environmentally friendly and aesthetically pleasing method. It can be used on its own or with soft engineering works in the middle or upper reaches, but may have to be used in conjunction with more costly engineering works in the downstream reaches. It is imperative that any rehabilitation strategies have contingency plans to deal with setbacks arising from flood damage during or after, the works are carried out. Constant maintenance, monitoring and repairs are essential and should be a major consideration in the planning and budgeting of such works.

8.5.5.4 Collection of Fine Sediment

Gravel benches are often constructed at the base of an eroding bank from materials removed from a point bar. For vegetation to grow on these bars, the bench must be stable and sedimentation needs to be encouraged. Bend stability and further sedimentation is best achieved by the use of jacks and groynes. Colonising shrubs and rushes are also useful for trapping sediment and it is important that species with an extensive root mats establish to stabilise the bench.

9. SUMMARY

This study has provided a scientific investigation into the fluvial geomorphology of the Nambucca River catchment. In doing so, a number of previously unknown factors have been addressed pertinent to the evolution of streams in southeastern Australia and the management of gravel-bed rivers in coastal NSW.

9.1 Late Quaternary Channel Change

The seven tributaries of the Nambucca catchment display differing records of fluvial activity in the terraces and floodplains. TL dating of 19 terrace samples indicates terraces ranging in age from 78 ka to 11 ka. Floodplain deposits were analysed using radiocarbon dating and 15 dates were obtained ranging in age from 2600-100 yrBP. These dates correspond with periods of fluvial activity obtained from several other catchments in southeastern Australia. For the Nambucca catchment five phases of development have been identified within the context of Oxygen Isotope Stages (OIS) since the last interglacial.

OIS 5 (Colleambally Phase 120-75 ka): The oldest TL date comes from Warrell Creek, the most stable of the tributaries. The relatively fine-grained geology of the Warrell Creek catchment has assisted in the preservation of older sedimentary units, as there is much less unconsolidated and erodible gravel stored in the floodplains. The TL age of 78.1±6.5 ka (W2732) for Site W3 corresponds with the end of OIS 5, a period of fluvial activity referred to as the Colleambally Phase in southeastern Australia (Page et al., 1996; Page and Nanson, 1996; Nanson et al., 2003).

OIS 3 (Kerarbury 55-35 ka and Gum Creek 32-25 ka Phases): Further terrace TL dates correspond to the two phases of fluvial activity identified within Stage 3 OIS. Site T4 on Taylors Arm has a terrace containing three dates between 55-50 ka, whilst Site D3 on Deep Creek has a terrace giving TL ages of 55-36 ka. These two terraces correspond with early to middle OIS 3, termed the Kerarbury Phase in southeastern Australia by Page et al. (1996). Site D3 also contains a terrace on the opposite bank dating 31-25 ka, which corresponds to late OIS 3, termed the Gum Creek Phase. The preservation of the

OIS 3 terraces at these locations is probably due to the fine-grained geology of Deep Creek which, like Warrell Creek, does not have much unconsolidated fine-gravel but cohesive alluvium and very limited reworking, whilst the wide valley floor at Site T4 (250 m) has prevented flow concentration.

OIS 2 (Yanco Phase 20-13 ka): The majority of TL dates recorded in the catchment are from OIS 2, more specifically from just after the LGM to the Holocene. This period from 20-13 ka has been termed the Yanco Phase by Page et al. (1996) and sites T9, N3, N6, S5, W2 and W3 all have terrace deposits dated within this Phase.

OIS 1 (Nambucca Phase 12-3 ka): Following the period of terrace development in the Yanco Phase, conditions altered sufficiently for the Nambucca to change, laterally eroding many of the Yanco terraces. During this period much of the coarse terrace material was re-worked into contemporary lower terraces and floodplains. The majority of the fine-grained sediment was probably moved to the coast. Such activity meant there is little preservation of any material reworked in the period 12-3 ka, now termed the Nambucca Phase (Nanson et al., 2003).

OIS 1 (Late Holocene 3 ka-0.1 ka): After 3 ka it is evident that fine-grained sediment began to deposit over the extensive basal gravels that covered the valley floors between the terrace remnants. As conditions altered and the floodplains grew vertically, dense forests became established, which would have encouraged further vertical accretion and periodic channel avulsion (Nanson, 1986; Brooks and Brierley, 2002). Material found in the uppermost floodplain gravels were dated (Sites T5, M4 and D3), giving ages of 2500-2000 yrBP. After about 2500-2000 BP there was no sign of lateral channel migration or other forms of substantial floodplain reworking or gravel accretion. Relatively narrow and deep palaeo-channels that date from about 1600 BP until the time of European settlement (around 130 BP) indicate periodic channel avulsion. A well-defined palaeochannel in the floodplain at Site 6 of Taylors Arm gave a basal date of 130±60 BP (Beta 101414). Another at Site 4 on North Arm gave a basal date of 440±60 BP (Beta 101415) while that within the floodplain at D3 has a clearly visible fine-grained channel fill within the floodplain dating at 1580±70 BP (Beta 101419) at the base and 1550±50 BP (Beta 101420) near the top.

The pattern of vertical accretion and periodic channel avulsion continued throughout the late Holocene to the arrival of settlers in the 1830's-1870's. The bed of the channels probably contained some gravel. However, the majority of the gravel transported and deposited during the Nambucca Phase remained buried beneath the floodplain and the channel.

9.2 Climate and Land Use Interactions

With the arrival of European settlers, modification of the Nambucca stream channels appears to have been limited to a combination of climate and land use interactions. Four distinct phases of land use and climate interactions have been identified, ultimately resulting in the present channel instability in the catchment.

Phase 1 (1830-1870): Settlers in the Nambucca valley in the 1830's arrived to conduct selective logging of the valuable red cedar (*Toona australis*) that proliferated in the floodplain forests of the catchment. This initial 40 years involved very little land clearance. Coupled with few recorded flood events, this probably ensured that the catchment was still well forested and stable when major land clearance and settlement commenced in the 1870's.

Phase 2 (1870-1896): Extensive clear felling of the forest to establish pasture commenced in the 1870's. Floodplains were particularly sought after and stream banks were denuded to improve stock access and to allow logs to be floated downstream. Clearance was well advanced by the 1890's when five of the largest floods recorded in the Nambucca occurred from 1890-1894. It is reasonable to suggest that land clearance and the removal of LWD caused channel incision at this time.

Phase 3 (1897-1947): The climate record shows this fifty-year period to have been relatively dry. Only four large floods occurred so the channel system was probably suspended between the effects of land clearance and the impact of a series of large floods after 1947. However, the 1942 aerial photographs indicate that nickpoints had already migrated upstream on South Arm, North Arm and Missabotti Creek. The relative

dryness of this period was probably the main reason that channels in the catchment remained relatively stable.

Phase 4 (1948-Present): A series of large floods occurred in the late 1940's and early 1950's that catastrophically altered the catchment streams. The size and frequency of floods during this period removed grasses and stripped floodplains of fine-grained sediment. Nickpoints retreated upstream and the stores of gravel that had been buried beneath the floodplains entered the streams. The Nambucca system now contained over-widened streams with lowered beds and was, for the first time in nearly 3000 years, transporting large amounts of quartz gravel that filled many of the pools. In an effort to curb the consequences of channel instability that brought new degradation with each flood, government authorities from the 1960's to the 1980's allowed the removal of gravel from the channel bars and the removal of woody debris. This only exacerbated the problem.

9.3 Effective Rehabilitation Measures

A number of recommendations are presented here on the assumption that, given the rural setting and limited government commitment, the management of the streams in the catchment will continue through the use of 'soft' engineering works that ensure low cost solutions using naturally occurring local materials.

Gravel Extraction: A combination of sediment size analysis, aerial photograph interpretation, channel bed comparisons and floodplain auguring has determined that the extensive gravel deposits found in the Nambucca streams originates from the floodplain stores and has not moved downstream from the headwaters. The removal of gravel from the system only exacerbates the problem of bed lowering, increasing bank erosion and thereby releasing additional gravel from the floodplain. Whilst the removal of gravel from bedrock pools and some inner bends is recommended where its continuation downstream will damage an otherwise stable reach, it is beneficial for this material to be relocated elsewhere in the system or be used to create an in-channel bench for other rehabilitation projects. Rehabilitation of the catchment's seriously degraded channels requires retention of existing gravel for the development of bars and benches.

Controlling Bed Levels: Nickpoints retreating up some tributaries in the Nambucca catchment indicate that bed lowering is still occurring. In conjunction with over-widening, the retreat of these nickpoints is very difficult to halt. An analysis of artificially constructed log sills showed them to be inadequate in most places. Rock ramps, however, provide a reliable method of channel management that acts to arrest the retreat of nickpoints.

Bank Erosion: Controlling bed lowering in the Nambucca is essential before any projects can be undertaken that will arrest bank erosion. Once the bed is stable the use of jacks, pin groynes and brush groynes is recommended to arrest bank retreat in straight reaches. These methods have proved inefficient on bends and the appropriate method for controlling bank erosion on outer bends has not been resolved. From a geomorphic perspective the deposition on the inner bend will continue as the outer bend retreats, and whilst this is a major inconvenience for landholders, the process is acting to restore sinuosity within the catchment.

Vegetation and Woody Debris Management: The use of native species in revegetation programs is desirable because many introduced species can dominate the riverine zone and inhibit the development of a stable plant community. The most suitable trees for colonisation of the riparian zone are casuarinas (*Casuarina cunninghamiana*), tea tree (*Leptospermum brachyandrum*), and bottle brush (*Callistemon viminalis*). All of these play a pioneering role in the same manner as willows. Sedges and rushes such as lomandra are also effective silt trapping supplements to the native trees mentioned above. Despite the common perceptions, casuarinas play a useful role in stream rehabilitation. As the pioneering species they have the potential as a monoculture to stabilise bars and benches. Selective pruning and thinning of them can result in a stabilised reach that supports the establishment of later successional species. Casuarinas are an opportunistic species and are an indicator of change; they are usually not the cause of change. Individual large casuarinas can grow precariously on the riverbanks and may need to be removed to prevent bank collapse. It is essential that vegetation is used to reduce and prevent stream bank erosion and, to facilitate the narrowing of overly wide channels. It is the most cost effective and environmentally acceptable method. It is imperative that rehabilitation strategies have contingency plans

to deal with any setbacks arising from flood damage during, or just after, the works are carried out. Constant maintenance, monitoring and repairs are essential and should be a major consideration in the planning and budgeting of such works.

9.4 Catchment Management Research Methodology

This study has been the first catchment management study in Australia to detail such channel and climate changes from the Late Pleistocene through to the present. In doing so it has provided evidence of Quaternary fluvial activity in order to explain the natural fluvial and sedimentary characteristics of the catchment. It then places in context the changes that have occurred since settlement, showing convincingly that anthropogenic influences are responsible for destabilisation of the streams in the Nambucca catchment. The clustering of large floods has been the trigger for catastrophic change, caused by vegetation removal by European settlers on the floodplains and in the channels.

The findings of this study have been the result of a methodology that has encompassed a variety of research techniques (Table 9.1). Through a combination of field, laboratory and archival research this study has been able to accurately identify the processes at work now and in the past. Although none of the techniques used here are new, the combination of techniques used here have not been used in any other study in Australia.

Table 9.1: Benefits of the various methodologies used in this study

METHOD	BENEFITS TO THIS STUDY
Cross Section Surveying	Channel widths and depths, floodplain width
Floodplain Auguring	Stratigraphy, radiocarbon/TL sampling, depth to bedrock/gravels, location of palaeo features
Floodplain Drilling	Stratigraphy, radiocarbon/TL sampling, depth to bedrock/gravels, location of palaeo features
TL dating of sediments	Age of terrace deposits
Radiocarbon dating of organic material	Age of floodplain deposits

Wolman Survey	Lithology and armour size for comparisons with downstream locations
Sediment Sieving	Grain size distribution and transportability of bedload, comparison of bed and floodplain gravel size
Vegetation Assessment	Interaction between vegetation and inferred processes at work, use in rehabilitation and future management
Aerial Photograph Analysis	Comparisons of channel change and catchment conditions over different time periods.
Analysis of Written and Oral History	Recorded anthropogenic interactions with the environment and historic account of channel change and climatic events.
Analysis of Climate and Hydrological Record	History of fluvial activity for comparison with information derived from the historical and sediment record
Monitoring of Rehabilitation Schemes	Evaluation of different techniques and suitability for different conditions

The findings of this study are now used in the management of streams in the mid-north coast of NSW and the recommendations have already produced a marked increase in the success of rehabilitation schemes. The methodology outlined for this study has helped to achieve a benchmark for the understanding of a single catchment in coastal southeastern Australia. Given the relatively short period since settlement in Australia, this methodology is forwarded to assist catchment managers understand the history and processes at work in the rapidly degrading streams they are required to manage.

REFERENCES

Abbe, T.B. and Montgomery, D.R. (1996) Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers; Research and Management, 12, 201-221.

Abbe, T.B., Brooks, A.P., Montgomery, D., Gippel, C.J. (2000) The geomorphic role of wood debris in the rehabilitation and management of fluvial environments. Paper presented at the International Conference on Wood in World Rivers. Oregon State University. October 23-27, 2000. Corvallis, OR.

Abernathy, B. and Rutherfurd, I.D. (1996) Vegetation and bank stabilisation in relation to changing channel scale. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, CRC for Catchment Hydrology.

Aitken, M.J. (1990) Science-based dating in archaeology, Longman Group, Essex, England.

Allison, G.B. (1975) Estimation of the water resources of a portion of the Gambier Plain South Australia using a new method for evaluating local recharge. Hydrology Symposium, Armidale, Nat Conf Pub 75/3, Institution of Engineers Australia.

Andrews, E.D. (1984) Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geological Society of America Bulletin, 95, 371-378.

Andrews, E.D. and Parker, G. (1987) Formation of a coarse surface layer as the response to gravel bed mobility. *In*. Thorne C.R., Bathurst I.C. and Hey R.D. (Eds.) Sediment transport in gravel bed rivers.

ANZECC, (1992), Australian Water Quality Guidelines for Fresh and Marine Waters. National Water Quality Management Strategy, ANZECC, Canberra, November 1992.

Bannens, R.J. (1981), Changes in Land Use and Hydrology of the Seven Valley. Report for Water for the Future Committee, Resource Engineering Department, University of New England.

Barr, N. and J. Cary (1992) Greening of a Brown Land: The Australian Search for Sustainable Land Use. South Melbourne: Macmillan.

Bishop, P., Young, R.W. and McDougall, I. (1985) Stream profile change and long-term landscape evolution: early Miocene and modern rivers of the east Australian highland coast, central New South Wales, Australia. Journal of Geology, 93, 455-74.

Blong, R.J. and Gillespie, R. (1978) Fluvially transported charcoal gives erroneous C14 ages for recent deposits. Nature, 271, 739-741.

Bonell, M. (1993) Progress in the understanding of runoff generation dynamics in forests, Journal of Hydrology, 150: 217-275.

Bonell, M,. Hendricks, M.R., Imeson, A.C. and Hazelhoff, L. (1984) The generation of storm runoff in a forested clayey drainage basin in Luxembourg, Journal of Hydrology, 7, 53-77.

Bonell, M. and Gilmour, D.A. (1978)The development of overland flow in a tropical rainforest catchment, Journal of Hydrology, 39, 365-382.

Bonell, M., Gilmour, D.A. and Cassel, D.S. (1991)The links between synoptic climatology and runoff response of rainforest catchments on the wet tropical coast of north east Queensland, in — Kershaw and Warren (eds), Australian National Rainforests - Study Report. Vol 2, Aust Heritage Commission, Canberra, pp 27-62.

Bonell, M., Gilmour, D.A. and Sinclair, D.F. (1981) Soil hydraulic properties and their effect on surface and sub-surface water transfer in a tropical rainforest catchment. Hydrol Sci Bul. 26, 1-18.

Boughton, W.C. (1970) Effects of Land Management on Quantity and Quality of Available Water; A Review, Report No 120, Water Research Laboratory, University of NSW. 330 pp.

Bren, L.J., Farrell, P.W. and Leitch, C.J. (1987) Use of weighted integral variables to determine the relation between rainfall intensity and storm flow and peak flow generation, Water Resources Research. 23, 1320-1326.

Bren, L.J., and Papworth, M. (1991)Early water yield effects of conversion of slopes of a eucalypt forest catchment to radiata pine plantation, Water Resources Research. 27, 2421-2428.

Brierley, G.J., Brooks, A.P. and Ferguson, R.J. (1995) Floodplain systems along the coastal plain of New South Wales. Australasian Sedimentologists Group Field Guide Series No.7. Geological Society of Australia, Sydney.

Brierley, G.J. and Fryirs, K. (1999) Tributary-trunk stream relations in a cut-and-fill landscape: A case study from Wolumla catchment, N.S.W., Australia. Geomorphology 28, 61-73.

Brierley, G.J. and Fryirs, K. (2000) River Styles in Bega Catchment, NSW, Australia: Implications for river rehabilitation. Environmental Management. 25(6):661-679.

Brierley, G.J. and Murn, C.P. (1997) European impacts on downstream sediment transfer and bank erosion in Cobargo catchment, New South Wales, Australia. Catena. 31, 119-136.

Brierley, G.J., Ferguson, R. and Woolfe, K. (1997) What is a fluvial levee? Sedimentary Geology. 114, 1-9.

Brizga, S.O. and Finlayson, B.L. (1990) Channel avulsion and river metamorphosis: The case of the Thompson River, Victoria, Australia. Earth Surface Processes and Landforms, 15, 391-404.

Brizga, S.O., Finlayson, B.L. and Chiew, F.H.S. (1993) Flood dominated episodes and river management: A case study of three rivers in Gippsland. Victoria. Hydrology and Water resources Symposium, Newcastle.

Brizga, S.O., Carden, M.F. and Craigie, N.M. (1996) The role of non-structural options in the management of laterally unstable streams in north-eastern Queensland. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Brookes, A. (1988) Channelised Rivers; Perspectives for Environmental Management, John Wiley and Sons, Chichester, U.K.

Brookes, A. (1995) Challenges and objectives for geomorphology in U.K. River management. Earth Surface Processes and Landforms, 20, 593-610.

Brookes A. (1996) River restoration in Northern Europe. In. River channel restoration: Guiding Principles for sustainable projects. Brookes, A. and Shields, F.D. (eds). Wiley, Chichester. U.K.

Brookes A. and Sear D.A. (1996) Geomorphological principles for restoring channels. In. River channel restoration: Guiding Principles for sustainable projects. Brookes, A. and Shields, F.D. (eds). Wiley, Chichester. U.K.

Brookes A. and Shields, F.D. (1996) Perspectives on river channel restoration. In. River channel restoration: Guiding Principles for sustainable projects. Brookes, A. and Shields, F.D. (eds). Wiley, Chichester. U.K.

Brooks, A.P. (1994) Vegetation and channel morphodynamics along the Lower Bega River. Macquarie University, School of Earth Sciences, Unpublished Honours Thesis.

Brooks, A.P. (1999a). Lessons for river managers from the fluvial tardis: direct insight into post-European channel changes from a near intact alluvial channel. Proceedings of the Second Australian Stream Management Conference, Adelaide. 121 – 128

Brooks, A.P. (1999b). Large woody debris and the geomorphology of a perennial river in southeast Australia. Proceedings of the Second Australian Stream Management Conference, Adelaide. 129 – 136

Brooks, A.P. (1999c) Pre- and Post-European disturbance river morphodynamics in East Gippsland. Australia. PhD Thesis, Macquarie University School of Earth Sciences, Unpublished.

Brooks, A.P., T.B. Abbe, M. Taylor, P. Gehrke, H. Jones, D. Outhet, and E. Avery. (2000). Experimental re-introduction of large woody debris for river rehabilitation and stabilization: an example from the Hunter Valley, southeastern Australia. In Abstracts of the International Conference on Wood in World Rivers. Oregon State University. October 23-27, 2000. Corvallis, OR. Pp. 113 - 118.

Brooks, A.P. and Brierley, G.J. (1997) Geomorphic responses of the lower Bega River to catchment disturbance, 1851-1926. Geomorphology, 18, 291-304.

Brooks, A.P. and Brierley, G.J. (2000) The role of European disturbance in the metamorphosis of lower Bega River. In: Finlayson, B.L. and Brizga, S.A. (Eds.). River Management: The Australasian Experience. Wiley. P221-246.

Brooks, A.P. and Brierley, G.J. (2002) Mediated equilibrium: The influence of riparian vegetation and wood on the long-term evolution and behaviour of a near pristine river. Earth Surface Processes and Landforms. 27, 343-367.

Brunsden, M. (1985) Scott of the Nmbukh: William Scott. first cedar merchamnt and white settler on the Nambucca River. North Coast NSW. Scotts Head.

Bryant, E.A. (1992) Last interglacial and Holocene trends in sea-level maxima around Australia: Implications for modern rates, Marine Geology, 108, 209-217.

Bull, W.B. and Scott, K.M. (1974) Impact of mining gravel from urban streambeds in the southwestern United States, Geology. 2, 171 - 174.

Bull, W.B. (1990) Stream terrace genesis: implications for soil development. Geomorphology, 18, 291-304.

Burkham, D. (1976) Hydraulic effects of changes to bottomland vegetation. United States Geological Survey Professional Paper, (655-J).

Burston, J. and Brown, W. (1996) Watercourse revegetation - Just a walk in the park. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Burston, J. and Good, M. (1996) Impact of European settlement on erosion and sedimentation in the Inman River catchment, South Australia. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Cassell D S, Gilmour, D A, and Bonell M, (1985), Catchment response and watershed management in the tropical rainforests in north-eastern Australia, Forest Ecology and Management. 10: 155 - 175.

Chang, H.H. (1987) Modelling fluvial processes in streams with gravel mining, *In,* Thorne C.R., Bathurst J.C. and Hey R.D.(Eds) Sediment Transport in Gravel Bed Rivers. John Wiley and Sons Limited, Chichester.

Chappell, J. (1983) Thresholds and lags in geomorphic changes. Australian Geographer, 15, 357-366.

Charlton, F.G., Brown, P.M. and Benson, R.W. (1978) The hydraulic geometry of some gravel rivers in Britain. Hydraulics Research Station, Wallingford.

Clifford, N. (1992) Formation of riffle-pool sequences: field evidence for an autogenic process. Sedimentary Geology. 85, 39-51.

Cohen, T. (1997) Recent channel change in a forested catchment. Jones Creek. East Gippsland. Victoria: The role of woody debris in channel recovery. Macquarie University School of Earth Sciences. Honours Thesis.

Cohen, T., Brierley, G.J. and Fryirs, K. (1996) Geomorphology and river ecology in southeastern Australia: an approach to catchment characterisation. Macquarie University, Graduate School of the Environment, Working Paper 9603.

Cornish, P.M.(1977) Changes in seasonal and annual rainfall in NSW. Search, 8, 38-40.

Cornish P.M. (1989) The Effects of Radiata Pine Plantation Establishment and Management on Water Yields and Water Quality: A Review. Technical Paper 49, Forestry Commission of NSW, Sydney, 53 pp.

Cornish, P.M. (1993) The effects of logging and forest regeneration on water yields in moist eucalypt forest in New South Wales, Australia. Journal of Hydrology. 150, 301-322.

Crapper, P.F, O'Loughlin, E.M. and Mackay, S.M. (1989) The hydrological effect of intensive logging operations on a small forested catchment near Eden, NSW, Proc Hydrology and Water Resources Symposium. IE Aust. Conf. Pub. NCP89/19, 444-448.

Cremer, K.W. (1994) Willows to spread rapidly by seed along rivers in SE Australia? CSIRO, Division of Forestry.

Cremer, K.W., Van Kraayenoord, C., Parker, N. and Streatfield, S. (1996) Willows spreading by seed: Implications for Australian river management. Australian Journal of Soil and Water Conservation, 8, 18-27.

Croke, J.C. (1996) Floodplain classification and its relevance to stream management. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

CSIRO (1992) Towards Healthy Rivers: A report to the Honourable Ros Kelly, Minister for Arts, Sport, the Environment and Territories. Division of Water Resources.

Darby, S.E. and Thorne, C.R. (1996) Numerical simulation of widening and bed deformation of straight sand-bed rivers, I: Model Development. Journal of Hydraulic Engineering, 122, 184-193.

Dawson, M.R. and Gardiner, V. (1987) River terraces: The general model and a palaeohydrological and sedimentological interpretation of the terraces in the lower Severn. In, Gregory, K.J., Lewin, J. and Thornes, J.B. (Eds) Palaeohydrology in Practice, Wiley and Sons, London.

Department of Land and Water Conservation (1995) State of the Rivers and Estuaries Report: Mid-North Coast Catchments 1994-1995, NSW Government.

Department of Land and Water Conservation (1996) Progress Report for the Nambucca River restoration works: August 1995 to May 1996. The Department. North Coast Region.

Department of Mineral Resources (1971) Dorrigo Geology Map. 1:250,000.

Department of Public Works, N.S.W. (1974) Report on Flood Mitigation Works Required in the Nambucca River Area, The Department.

Department of Public Works NSW (1980) Nambucca River Flood History 1890-1979. The Department.

Department of Water Resources, NSW (1990) Sand and gravel extraction from non-tidal rivers in NSW: A Discussion, The Department.

Department of Water Resources (1994) Draft Management Plan: Control of Erosion and Gravel Extraction Nambucca River and Missabotti Creek. The Department.

Department of Water Resources, NSW (1995) Nambucca River Restoration Program. The Department.

Dodson, J.R. (1986) Palaeoclimates since 12 ka near the summer/winter rainfall boundary in Southeastern Australia. In, International Union for Quaternary Research XII: Programs and Abstracts, 158p.

Doyle, C.J., Nanson, G.C. and Perrens, S.J. (1999) European disturbance of the Nambucca River Catchment: Lessons for the management of gravel-bed rivers in southeastern Australia. Proceedings of the Second Australian Stream Management Conference, Adelaide. 163 – 169

Ecology Lab Pty Ltd (1997) Aquatic Ecology: Nambucca District Water Supply Augmentation. Draft Report for Department of Public Works and Services, January 1997.

Eddie, M. (1996) Summary of Soil Landscapes of the Nambucca Catchment Management Area, Department of Land and Water Conservation NSW.

Erskine, W.D.(1986) River metamorphosis and environmental change in the Macdonald Valley, New South Wales since 1949. Australian Geographical Studies. 24, 88-107.

Erskine, W.D. (1990) Hydrogeomorphic effects of river training works: the case study of the Allyn River, NSW. Australian Geographical Studies. 62-76.

Erskine, W.D. (1992) An investigation of sediment sources in the Genoa River Catchment, East Gippsland River Management Board, 88p.

Erskine, W.D. (1994) Late Quaternary Alluvial History of Nowlands Creek, Hunter Valley, NSW. Australian Geographer, 25, 50-60.

Erskine, W.D. and Bell, F.C. (1982) Rainfall, floods and channel change on the upper Hunter. Australian Geographical Studies, 20, 183-196.

Erskine, W.D. and Melville, M.D. (1983) Impact of the 1978 floods on the channel and floodplain of the Lower Macdonald River, NSW. Australian Geographer. 15, 284-292.

Erskine, W.D., Geary, P.M. and Outhet, D.N. (1985) Potential impacts of sand and gravel extraction on the Hunter River, NSW. Australian Geographical Studies, 23, 71-86.

Erskine, W.D. and Warner, R.F. (1988) Geomorphic effects of alternating flood and drought dominated regimes on New South Wales coastal rivers. In Warner, R.F., editor, Fluvial Geomorphology of Australia. Sydney: Academic Press, 223-244.

Erskine, W.D. and White, L.J. (1996) Historical river metamorphosis of the Cann River, East Gippsland, Victoria. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Erskine, W.D., Tennant, W.K. and Tilleard, J.W. (1996) Sustainable Sand and Gravel Extraction: The Development of a Management Plan for the Goulburn River, Victoria, Proceedings of the First National Conference on Stream Management in Australia, Merrijig.

Erskine, W.D. and Livingstone, E.A. (1999). In-channel benches: the role of floods in their formation and destruction on bedrock-confined rivers. In: A.J. Miller and A. Gupta (eds). Varieties of Fluvial Form. Pp. 445-475. Wiley Chichester.

Eyles, R.J. (1977) Changes in drainage networks since 1820, Southern Tablelands, NSW. Australian Geographer, 13, 377-386.

Ferguson, R.I. (1987) Hydraulic and sedimentary controls on channel pattern. River channels: Environment and Processes, K.Richard (ed), Blackwell, U.K., 129-158.

Ferguson R.I., Hoey T., Wathen S. and Werritty A. (1996) Field evidence for rapid downstream fining of river gravels through selective transport. Geology. 24,179-182.

Ferguson, R.J. and Brierley, G.J. (1999a) Downstream changes in valley confinement as a control on floodplain morphology, lower Tuross River, New South Wales, Australia. In: Miller, A.J. (Ed.). Varieties of Fluvial Form. Wiley. P377-407.

Ferguson, R.J. and Brierley, G.J. (1999b) Levee morphology and sedimentology along the lower Tuross River, southeastern Australia. Sedimentology. 46, 627-648.

Fetherston, K.L., Naiman, R.J. and Bilby, R.E. (1995) Large woody debris, physical processes and riparian forests development in montane river networks of the Pacific Northwest: Proceedings of the 26th Binghampton Symposium in Geomorphology. Geomorphology, 13, 133-144.

Finlayson, B.L. and Brizga, S.O. (1995) The oral tradition, Environmental change and river basin management: Case studies from Queensland and Victoria, Australian Geographical Studies, 33, 180-192.

Flannery, T. (1994) The Future Eaters. Reed Books, Melbourne, 423p.

Flemming, P.M., Wells, A.T., and McKenzie, N.M. (1991) The Effects of Landuse on the Water Resource: An Annotated Bibliography. Land and Water Resources Research and Development Corporation, National River Health Project 40/91, LWRRDC, Canberra, 331 pp.

Frankenburg, J., Tennant, W.K. and Tilleard, J.W. (1996) Mechanisms of stream bank erosion: The results of five years of bank profile monitoring on the River Murray. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Friedman, J.M., Osterkamp, W.R. and Lewis, W.M. Jr. (1996) The role of vegetation and bed-level fluctuations in the process of channel narrowing. Geomorphology, 14, 341-351.

Friend P.F. (1993) Control of river morphology by the grain-size of sediment supplied. Sedimentary Geology, 85, 171-177

Fryirs, K.A. (2001) A Geomorphic Approach for Assessing the Geomorphic Condition and Recovery Potential of Rivers in Bega Catchment. South Coast. New South Wales. Australia. Unpublished PhD Thesis, Department of Physical geography, Macquarie University.

Fryirs, K and Brierley, G.J. (1998) The character and age structure of valley fills in upper Wolumla Creek catchment, South Coast, New South Wales, Australia. Earth Surface Processes and Landforms 23, 271-287.

Fryirs, K. and Brierley, G.J. (1999). Slope channel decoupling in Wolumla catchment, South Coast, New South Wales, Australia : the changing nature of sediment sources since European settlement. Catena. 35, 41-63.

Fryirs, K. and Brierley, G.J. (2000). A geomorphic approach for identification of river recovery potential. Physical Geography. 21(3), 244-277.

Fryirs, K. and Brierley, G.J. (2001) Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: Implications for geomorphic river recovery. Geomorphology. 38, 237-265.

Gaddes, A.S. (1990) Red cedar. our heritage: a personal account of the lives and times of the men and women who worked in the red cedar industry. Wyndham Observer, Nanango, Queensland.

Galay, V.J. (1983) Causes of riverbed degradation, Water Resources Research. 19, 1057-1090.

Gale, S.J., Haworth, R.J. and Pisanu, P.C. (1995) The 210Pb chronology of late Holocene deposition in an eastern Australian lake basin. Quaternary Science Reviews 14, 395-408

Gale, S.J. and Pisanu, P.C. (2001) The late-Holocene decline of Casuarinaceae in southeast Australia. The Holocene 11, 485-490.

Gardiner, J. (1996) The management of stream erosion and sedimentation - An interactive community driven process. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Geraghty, P. and Vollebergh, P. (1996) A schematic history of waterway management in Victoria. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Gessler, P.E., Moore, I.D., McKenzie, N.J., and Ryan, P.J. (1995). Soil-landscape modelling and spatial prediction of soil attributes. International Journal of Geographic Information Systems. 9, 421-32.

Gilmour D A, Bonell M and Sinclair D F, (1980), An investigation of storm drainage processes in a tropical rainforest catchment. Australian Water Resources Commission Tech Paper 56, Australian Government Printing Service, Canberra, 93 pp.

Gippel, C.J., Finlayson, B.L. and O'Neil, I.C. (1996) Distribution and hydraulic significance of large woody debris in a lowland river. Hydrobiologia, 318, 179-194.

Good, M. and Burston, J. (1996) No involvement, no commitment, no change! -Involving the community in watercourse management. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Goudie, A. (1993) Human Impact on the natural environment. Blackwell Publishers, London

Graecen, W.H. and Sands, R. (1980) Compaction of forest soils: A review. Aust Soil, 18: 163-89.

Graeme, D. and Dunkerley, D.L. (1993) Hydraulic resistance by the River Red Gum, Eucalyptus Camaldulensis, in ephemeral desert streams. Australian Geographical Studies, 31, 141-154.

Graf, W.L. (1977) Geomorphic impact of changes in riparian vegetation in the canyons of the Colorado Plateau. Geomorphology: Human Induced Changes. at the 1977 Annual meeting of the Association of American Geographers, Salt Lake City, Utah, April 14-27.

Grayson R.B., Argent R.M., Nathan, R.J., McMahon, T.A. and Mein, R.G. (1997) Hydrological Recipes: Estimation Techniques in Australian Hydrology. Cooperative Research Centre for Catchment Hydrology, Melbourne.

Gregory, K.J. and Gurnell, A.M. (1988) Vegetation and River Channel form and process. In, Biogeomorphology, Viles, H.A. (ed), Basil Blackwell Ltd, Oxford, 11-42.

Grissinger, E.H. (1982) Bank erosion of cohesive materials.In, Gravel-Bed Rivers, Hey, R.D., Bathurst, J.C. and Thorne, C.R. (eds), Chichester, 273-287.

Gurnell, A.M. and Sweet, R. (1998) The distribution and magnitude of large woody debris accumulations and pools in relation to woodland stream management. Earth Surface Processes and Landforms, 23, 1101-1121.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J. (2000) Wood storage within the active zone of a large European gravel-bed river. Geomorphology, 34, 55-72.

Gurnell, A.M., Piegay, H., Swanson, F. and Gregory, S. (2002) Large wood and fluvial processes. Freshwater Biology, 47, 601-619.

Gutteridge, Haskins and Davey (1981) New South Wales Coastal Rivers Floodplain Management Studies: Nambucca Valley. Gutteridge, Haskins and Davies.

Hadley, R.F. (1961) Influence of riparian vegetation on channel shape, northeastern Arizona, United States Geological Survey Professional Paper 424-C.

Haltiner, J.P., Kondolf, G.M. and Williams, P.B. (1996) Restoration approaches in California. In. River channel restoration: Guiding Principles for sustainable projects. Brookes, A. and Shields, F.D. (eds). Wiley, Chichester. U.K.

Hairsine, P. (1996) Comparing grass filter strips and near natural riparian forests for buffering intense hillslpopes sediment sources. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Haworth, R.J. (1994) European impacts on lake sedimentation in upland Eastern Australia: case studies from the New England Tablelands of New South Wales. Unpublished PhD thesis, University of New England, Armidale.

Haworth, R.J., Gale, S.J., Short, S.A. and Heijnis, H. (1999) Land use and lake sedimentation on the New England Tablelands of New South Wales, Australia. Australian Geographer, 30, 51-73.

Hean, D.S. and Nanson, G.C. (1987) Serious problems using equations to estimate bedload yields for coastal rivers in New South Wales. Australian Geographer, 18, 114-124.

Heede, B.H. (1972) Influences of a forest on the hydraulic geometry of two mountain streams. Water Resources Bulletin, 8, 523-530.

Heede, B.H. (1985) Channel adjustments to the removal of log steps: an experiment in a mountain stream. Environmental Management, 9, 427-432.

Henry, H.M. (1977) catastrophic channel changes in the Macdonald valley, New South Wales, 1949-1955. Journal and proceedings. Royal Society of New South Wales, 110, 1-16.

Hewlett, J.D., Fortson, J.C., and Cunningham, G.B. (1984) Additional tests on the effect of rain intensity on streamflow and peak flow from wild land basins, Water Resources Research, 20, 985-989.

Hey, R.D. and Thorne, C.R. (1983) Hydraulic geometry of mobile gravel-bed rivers. Proceedings of the second international symposium on river sedimentation. Nanjing. China. Water resource and Electric Power Press.

Hey, R.D. and Thorne, C.R. (1984) Stable channels with mobile gravel beds. Journal of Hydraulic Engineering, 112, 671-689.

Hickin, E.J. (1984) Vegetation and river channel dynamics. Canadian Geographer, 28, 11-126.

Hickin, E.J. and Page, K.J. (1971) The age of valley fills in the Sydney basin. Search. 2, 383-384.

Hirsch, P.J and Abrahams, A.D. (1996) The properties of bed sediments in pools and riffles. Journal of Sedimentary Petrology. 51, 757-760.

Hoey, T.B. and Ferguson, R.I. (1994) Numerical simulation of downstream fining by selective transport in gravel bed rivers: Model development and illustration. Water Resources Research. 30(7), 2251-2260.

Hopley, D. (1987) Holocene sea level changes in Australia and the southern Pacific. In, Devoy, R.J.N. (ed). Sea surface studies: a global view, Croom Helm, London, 375-408.

Holmes, J.W. and Sinclair, J.A. (1986) Water yield from some afforested catchments in Victoria, Proceedings of Hydrology and Water Resources Symposium, Nat Conf Pub 86/13, 214-218, Institute of Engineers Australia, Canberra.

Holmes and Colville (1968) On the water balance of grassland and forest, Trans 9th Congress Int Soil Sci Soc, 1, 39.

Huang, H.Q. and Nanson, G.C. (1997) Vegetation and channel variation: A case study of four small streams in southeastern Australia. Geomorphology, 18, 237-249.

Hughes, P.J. and Sullivan, M.E. (1981) Aboriginal burning and late Holocene geomorphic events in eastern NSW. Search, 12, 277-278.

Hughes, R. (1984) The Fatal Shore, Pan Books, London.

Hupp, C.R. and Osterkamp, W.R. (1996) Riparian vegetation and the fluvial geomorphic process, Geomorphology, 14, 277-295.

Ikeda, S., Parker, G. and Kimura, Y. (1988) Stable width and depth of straight gravel rivers with heterogenous bed materials. Water Resources Research. 24, 713-722.

Ikeda, S. and Izumi, N. (1990) Width and depth of self-formed straight gravel-bed rivers with bank vegetation. Water Resources Research, 26, 2353-2364.

Institution of Engineers, Australia, (1987), Australian Rainfall and Runoff. 2 Vols, Institute of Engineers Australia, Canberra.

Jain, S.C. and Park, I. (1989) Guide for estimating riverbed degradation. Journal of Hydraulic Engineering, 356-366.

Jayasuriya M D A and O'Shaughnessy P J, (1988), Effects on water yield of uniform thinning and patch cutting treatment in a forest of regeneration Mountain Ash. Third Progress Report: North Maroondah. Melbourne Metro Board of Works,

Jones, G., Robertson, A., Forbes, J. and Hollier, G. (1990) Dictionary of Environmental Science, Harper-Collins, Glasgow U.K.

Julien, P.Y. and Wargadalam, J. (1995) Alluvial channel geometry: Theory and applications. Journal of the Hydraulics Division (Proceedings of the American Society of Civil Engineers), 121, 312-325.

Kapitze, R., Smithers, S. and Lowry, J. (1996) Channel change, bank stability and managementfor north Queensland coastal streams. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Keller, E.A. (1975) Channelisation: A search for a better way. Geology, 246-248.

Keller, E.A. (1978) Pools, riffles and channelisation. Environmental Geology, 2, 119-127.

Kellerhals, R., and Bray, D. I. 1971. “Sampling Procedures for Coarse Fluvial Sediments,” Journal of the Hydraulics Division, American Society of Civil Engineers, Vol 97, No. HY8, pp 1165-1180.

Kershaw, A.P. and Nanson, G.C. (1993) The last full glacial cycle in the Australian region, Global and Planetary Change, 7,1-9.

Kirkup, H.(1996) A preliminary investigation of streamflow variability in coastal NSW using wavelet analysis techniques. Macquarie University, School of Earth Sciences, Unpublished Honours Thesis.

Kirkup, H., Brierley, G.J., Brooks, A. and Pitman, A. (1998) Temporal variability of climate in southeastern Australia - a reassessment of flood- and drought-dominated regimes. Australian Geographer. 29, 241-255.

Kirkup, H., Pitman, A. Hogan, J. and Brierley, G.J. (2001) An initial analysis of river discharge and rainfall in coastal New South Wales, Australia using wavelet transforms. Australian Geographical Studies. 39, 313-334.

Koehn, J.D., Brierley, G.J., Cant, B.L. and Lucas, A.M. (2001) River Restoration Framework. Land and Water Australia Occasional Paper 01/01. Canberra, Australia.

Kouwan, N. and Li, R.M. (1980) Biomechanics of vegetative channel linings. Journal of the Hydraulics Division (Proceedings of the American Society of Civil Engineers), 106, 1085-1103.

Kouwan, N. (1988) Field estimation of the biomechanical properties of grass. Journal of Hydraulic Research, 26, 559-568.

Knighton, A.D. (1984) Fluvial forms and processes. London, Edward Arnold.

Kondolf, G.M. and Swanson, M.L. (1993) Channel adjustments to reservoir construction and gravel extraction along Stony Creek, California. Environmental Geology, 21, 256-269.

Kondolf, G.M. (1995) Managing bedload sediments in regulated rivers: Examples from California, USA. Geophysical Monograph. 89: 165-176.

Kondolf, G.M. (1996) Letter to the Mendocino County Planning Commission and supervisors.

Kondolf, G.M., Smeltzer, M. and Kimball, L. (2002) Gravel Mining and Dredging Issues. White paper prepared for the Washington Departments of Fish and Wildlife, Ecology, and Transportation, Olympia. Report CEDR-_-01, University of California, Berkeley.

Kuczera, G. (1975) Predictions of Water Yield Reductions Following Bushfire in Ash — Mixed Species Eucalypt Forest. Report MMBW-W-0014, Melbourne Metro Board of Works, 163 pp

Lagasse, P.F., Winkley, B.R., and Simons, D.B. (1980) Impact of gravel mining on river system stability, Journal of Waterways and Ports Coastal Ocean Proceedings American Society of Civil Engineers. 106, 389-404.

Lamplugh, G.W. (1914) Taming of the streams. Geographical Journal, 43, 651-656.

Langford, K.J. (1976) Changes in yield of water following a bushfire in a forest of Eucalyptus regnans, J Hydrology, 29, 87-114.

Langford, K.J. and O'Shaughnessy P.J. (1980a), A Case Study of the Maroodnah Catchment. Report MMBW-W-0011, Melbourne Metro Board of Works, 175 pp

Langford, K.J. and O'Shaughnessy, P.J. (1980b), Second Progress Report Coranderrk Catchment. Report MMBW-W-0010, Melbourne Metro Board of Works, 175pp

Langford K.J. and Lewis R.A. (1975) Detection of change in sequences of hydrologic data. Proc Hydrol Symp, Institute of Engineering Australia, Sydney, 80-84.

Langford, K.J.and O'Shaughnessy, P.J. (1979) Forest management and water supply — A progress report of the MMBW research program. Proc Hydrol and Water resources Symposium, Institute of Engineers Australia Nat Conf Pub NCP79/10, 220-224.

Lee H-Y., Fu D-T. and Song M-H. (1993) Migration of a rectangular mining pit composed of uniform sediments. Journal of Hydraulic Engineering,119, 64-80.

Leopold, L.B. (1951) Alluvial flats near Gallup, New Mexico. American Journal of Science, 249, 152-168.

Leopold, L.B., Wolman, M.G. and Miller, J.P. (1964) Fluvial processes in geomorphology. W.H. Freeman and Co.,San Francisco.

Li, R.M. and Shen, H.W. (1973) Effects of tall vegetation on flow and sediment. Journal of the Hydraulics Division (Proceedings of the American Society of Civil Engineers),99, 793-814.

Lyall and Macoun Consulting Engineers (1996) Nambucca Valley Catchment and River Management Study: Inception Report. Lyall and Macoun, Sydney.

Mackin, J.H. (1956) Cause of braiding by a graded river. Geological Society of America Bulletin, 67, 1717-1718.

McMinn, A. (1992) Quaternary coastal evolution of northern New South Wales, Australia, based on dinoflagellates and pollen. Quaternary Research, 38, 347-358.

Magilligan, F.J. and McDowell, G.F. (1996) Stream channel adjustments following the elimination of cattle grazing. Water Resources Bulletin.

Malanson, G.P. and Butler, D.R. (1990) Woody debris, sediment, and riparian vegetation of a subalpine river, Montana, USA, Arctic and Alpine Research, 22, 183-194.

Martin, P. and Lockie, S. (1993) Environmental information for total catchment management: Incorporating local knowledge. Australian Geographer, 24, 74-85.

Masterman, R. and Thorne, C.R. (1992) Predicting the influence of bank vegetation on channel capacity. Journal of Hydraulic Engineering, 118, 1052-1058.

Megahan, W.F. (1977) Reducing erosional impacts of roads, in- Kunkle (ed), Guidelines for Watershed Management, FAO Conservation guide, FAO Rome, pp 237 — 261.

Mein, R. G., Jayasuriya, L.N.N., Jayasuriya, M.D.A. and O'Shaughnessy, P.J. (1993) Simulation of water yield to evaluate the impact of timber harvesting strategies for the Thompson catchment, Proceedings of Hydrology and Water Resources Symposium, Nat Conf Pub 93/14, 75-80, Institute of Engineers Australia, Canberra

Melville, M.D. and Erskine, W.D. (1986) Sediment remobilisation and storage by discontinuous gullying in humid southeastern Australia. In, Drainage Basin Sediment Delivery; Proceedings of the Alberquerque Symposium August 1996, Intl. Assoc. Hydrol. Publ. No. 159, 277-286.

Melzer, A.D. (1962) A Preliminary Report on the Callide Valley Investigation. Irrigation and Water Supply Commission. Queensland. Internal Report.

Millar, R.G. and Quick, M.C. (1993) Effect of bank stability on geometry of gravel rivers. Journal of Hydraulic Engineering, 119, 1343-1363.

Millar, R.G. and Quick, M.C. (1996) Assessment of river channel stability. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Millar, R.G. and Quick, M.C. (in press) Stable geometry of gravel-bed rivers with cohesive banks. Journal of Hydraulic Engineering.

Milne, J.A. (1982) Bed-material size and the pool-riffle sequence. Sedimentology. 29, 267-278.

Mount, J. (1996) Letter to the Mendocino County Planning Commission and supervisors.

Murgatroyd, A.L. and Ternan, J.L. (1983) The impact of afforestation on streambank erosion and channel form. Earth Surface Processes and Landforms, 8, 357-369.

Murn, C.P. (1994) The pattern and timing of bank erosion - 1957 to 1994. Cobargo Catchment. South Coast. New South Wales. Macquarie University School of Geosciences, Unpublished Honours Thesis.

Nagel, F. (1995) The effectiveness of bank stabilisation works on Baerami Creek. Macquarie University School of Earth Sciences. Honours Thesis.

Nakamura, F. and Swanson, F.J. (1993) Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in Western Oregan, Earth Surface Processes and Landforms, 18, 43-61.

Nambucca Valley Association (1990) Comments on NSW Water Resources Discussion Paper on Sand and Gravel Extraction on Non-Tidal Rivers in NSW. Unpublished.

Nanson, G.C. and Beach, H.F. (1977) Forest succession and sedimentation on a meandering river floodplain, northeast British Columbia, Canada. Journal of Biogeography, 4, 229-251.

Nanson, G.C. (1980) Point bar and floodplain formation of the meandering Beatton River, northeast British Columbia, Canada. Sedimentology, 27, 3-29.

Nanson, G.C. (1981) New evidence of scroll bar formation on the Beatton River. Sedimentology, 28, 889-891.

Nanson, G.C. (1986) Episodes of vertical accretion and catastrophic stripping: a model of disequilibrium floodplain development. Geological Society of America Bulletin, 97, 1467-1475.

Nanson, G.C. and Young, R.W. (1981a) Downstream reduction in rural channel size with contrasting urban effects in small coastal streams of southeastern Australia. Journal of Hydrology, 52, 239-255.

Nanson, G.C and Young, R.W. (1981b) Downstream reduction of rural channel size with contrasting urban effects in small coastal streams of southeastern Australia, Journal of Hydrology, 52, 239-255.

Nanson, G.C. and Young, R.W. (1987) Comparison of thermoluminescence and radiocarbon age determinations from late-Pleistocene alluvial deposits near Sydney, Australia. Quaternary Research, 27, 263-269.

Nanson, G.C. and Young, R.W. (1988) Fluviatile evidence for a period of Late-Quaternary climate change in coastal southeastern Australia, Palaeogeography. Palaeoclimatology. Palaeoecology, 66, 45-61.

Nanson, G.C. and Erskine, W.D. (1988) Episodic changes of channels and floodplains on coastal rivers in New South Wales. In Warner, R.F., editor, Fluvial Geomorphology of Australia. Sydney: Academic Press, 201-221.

Nanson, G.C. and Croke, J.C. (1992) A genetic classification of floodplains. Geomorphology, 4, 459-486.

Nanson, G.C., Price, D.M. and Short, S.A. (1992) The wetting and drying of Australia over the past 300Ka. Geology, 20, 791-794.

Nanson, G.C., Barbetti, M. and Taylor, G. (1995) River stabilisation due to changing climate and vegetation during the Quaternary in Western Tasmania, Australia. Geomorphology, 13, 145-158.

Nanson, G.C., Price, D.M. and Chen, X.Y. (1995) Aeolian and fluvial evidence of changing climate and wind patterns during the past 100 ka in the western Simpson Desert, Australia. Palaeogeography. Palaeoclimatology. Palaeoecology, 66, 45-61.

Nanson, G.C. and Doyle, C. (1999) Landscape stability, Quaternary climate change and European degradation of coastal rivers in southeastern Australia. In I. Rutherfurd and R Bartley (Eds), Second Austalian Stream Management Conference Proceedings, Adelaide, Vol. 2, pp.473-479.

Nanson, G.C., Cohen, T.J., Doyle, C.J. and Price, D.M. (2003) Alluvial evidence of late-Quaternary climate and flow-regime changes on the coastal rivers of New South Wales, Australia. In K.J Gregory and G. Benito (Eds), Palaeohydrology: Understanding Global Change, Wiley, Chichester (in press).

National Research Council (1992) Restoration of aquatic ecosystems. National Academy Press, Washington D.C, USA, 552p.

Neill, C.R. and Hey, R.D. (1982) Gravel Bed Rivers: Engineering Problems. In. Gravel Bed rivers: Fluvial processes. engineering and management. Thorne, C.R. and Hey, R.D. (Eds). Wiley, London.

Nevins, T.H.F. (1969) River Training - the single thread channel. N.Z Engineer, 367-373.

New South Wales Dept. Of Public Works (1980) Nambucca River Flood History 1890 - 1979, The Department.

New South Wales Landcare Working Party (1991) Decade of Landcare: Draft Plan for NSW. State catchment co-ordinating committee, Sydney.

Nicholls, N. and Lavery, B. M. 1992. Australian rainfall trends during the twentieth century. International Journal of Climatolology, *12*, 153–63.

North Arm Landcare Group (1990) Submission to NSW Water Resources: Sand and Gravel Extraction from Non-Tidal Rivers in NSW. Unpublished.

Nott, J.F. (1992) Long-term drainage evolution in the Shoalhaven catchment, southeast highlands, Australia. Earth Surface Processes and Landforms, 17, 361-374.

Nott, J.F. and Price, D. (1991) Late Pleistocene to early Holocene aeolian activity in the middle and upper Shoalhaven catchment, southeastern New South Wales. Australian Geographer, 22,168-177.

Nott, J.F., Price, D.M., and Bryant, E.A. (1996) A 30,000 year record of extreme floods in tropical Australia from relict plunge pool deposits: Implications for future climate change. Geophysical Research Letters, 23, 379-382.

Nott, J. F., Bryant, E. A. and Price, D. M. (1999) Early Holocene aridity in tropical northern Australia. The Holocene, 9, 231-236

Olive, L.G. and Reiger, W.A. (1986) Low Australian sediment yields - a question of inefficient sediment delivery ? IAHS Publication. 159, 355-366.

Olive, L.G. and Reiger, W.A. (1988) Problems in assessing the impacts of different forestry practices on coastal catchments in New South Wales. In Warner, R.F., editor, Fluvial Geomorphology of Australia. Sydney: Academic Press, 283-302.

Olley, J. M., Caitcheon, G. G. & Murray, A. S. (1998). The distribution of apparent dose as determined by optically stimulated luminescence in small aliquots of fluvial quartz: implications for dating young sediments. Quatern. Sci. Rev. (Quatern. Geochronol.) 17, 1033–1040.

O'Shaughenessy P J and Jayasuriya M D A, (1987), Managing the ash forests for water production in Victoria, Proc Inst Foresters Aust, 1987 Biennial Conf, Perth, 437 — 463.

O'Shaughenessy, P.J. and Jayasuriya, M.D.A. and Aney, S.T. (1989) A review of the catchment management policies of three major water supply authorities with special reference to recent MMBW forest hydrology research results, Proc Inst Foresters Aust. 1989 Biennial Conf, Leura, 107 — 122.

Osman, A.M. and Thorne, C.R. (1988) Riverbank Stability Analysis. I: Theory. Journal of Hydraulic Engineering, 114, 134-150.

Outhet, D. (1996) Riverwise: Educating the community about river management. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Outhet, D., Brooks, A., Hader, W., Corlis, P., Raine, A., Broderick, T., Avery, E., Babakaiff, S. (2001) 'Gravel bed river riffle restoration in New South Wales'. In: Rutherfurd, I., Sheldon, F., Brierley, G. and Kenyon, C. (Editors), Proceedings of the 3rd Austraian Stream Management Conference, Brisbane, 27 - 29 August 2001, pp. 483 - 487.

Page, K.J. (1994) Late Quaternary Stratigraphy and chronology of the Riverine Plain. Southeastern Australia, University of Wollongong, Unpublished PhD Thesis.

Page, K.J. and Nanson, G.C. (1996) Stratigraphic architecture resulting from Late-Quaternary evolution of the Riverine Plain, south-eastern Australia. Sedimentology, 43, 927-945.

Page, K.J., Nanson, G.C. and Price, D.M. (1996) Chronology of Murrumbidgee Palaeochannels on the Riverine Plain, Southeastern Australia. Sedimentology, 43, 927-945.

Paola C., Parker G., Seal R., Sinha S.K., Southard J.B. and Wilcock P.R. (1992) Downstream fining by selective deposition in a laboratory flume. Science. 258,1757-1760.

Patrick, D.M., Smith, L.M. and Whitten, C.B. (1982) Methods for studying accelerated fluvial change. In. Gravel Bed rivers: Fluvial processes. engineering and management. Thorne, C.R. and Hey, R.D. (Eds). Wiley, London.

Pasche, E. and Rouve, G. (1985) Overbank flow with vegetatively rough floodplains. Journal of Hydraulic Engineering, 111, 1262-1278.

Patton, P.C. and Schumm, S.A. (1980) Ephemeral-stream processes: implications for studies of Quaternary valley fills. Quaternary Research, 15, 24-43.

Pearce, A.J., Stewart, M.K. and Sklash, M.G. (1986) Storm runoff generation in humid headwaters catchments — 1: Where does all the water come from?, Water Resources Research. 22, 1262-1272.

Perrens, S J, (1986), *Conversion of forest land to annual crops: The Australian experience*, in Land Use, Watersheds and Planning in the Asia-Pacific Region, 112-137, FAO, Bangkok.

Petit, F., Poinsart D. and Bravard, J-P. (1996) Channel incision, gravel mining and bedload transport in the Rhone river upstream of Lyon, France. Catena, 26, 209-226.

Petryk, S. and Bosmajian, G. (1975) Analysis of flow through vegetation. Journal of the Hydraulics Division (American Society of Civil Engineers), 101, 871-873.

Petts, G.E. (1984) Sedimentation within a regulated river. Earth Surface Processes and Landforms, 9, 125-134.

Pickup, G. (1974) Downstream variations in morphology, flow conditions and sediment transport in eroding channels. Zeitschrift fur Geomorphologie. 19, 443-459.

Pickup, G. (1976) Geomorphic effects of changes in river run-off, Cumberland Basin, NSW. The Australian Geographer. 13, 188-193.

Pietch, T. (in prep) Late Quaternary History and Geomorphology of the Gwydir River Fan. PhD Thesis, University of Wollongong School of Geosciences.

Pittock, A.B. (1975) Climatic change and the patterns of variation in Australian rainfall. Search, 6, 498-504.

Pizzuto, J.E. (1995) Downstream fining in a network of gravel bedded rivers. Water Resources Research. 31, 753-759.

Pressland, A.J. (1981) The Effect of Land use on the Hydrology and Productivity of Small Rural Catchments, Ph D Thesis, University of New England, November 1981.

Price, D.M. (1994) TL signatures of quartz grains of different origin. Radiation Measurements, 23, 413-417.

Prosser, I.P. (1991) A comparison of past and present episodes of gully erosion at Wangrah Creek, Southern Tablelands, New South Wales. Australian Geographical Studies, 29, 139-154.

Prosser, I.P. and Slade, C.J. (1994) The role of valley floor vegetation in gully initiation, south eastern Australia. Geology, 22, 1127-1130.

Prosser , I.P., Chappell, J. and Gillespie, R. (1994) Holocene valley aggradation and gully erosion in headwater catchments, southeastern highlands of Australia. Earth Surface Processes and Landforms, 19, 465-480.

Public Works Department (1980) Nambucca River Flood History 1890 - 1979, PWD, Coffs Harbour, 114 pp.

Public Works Department (1981) Nambucca River May 1980 Flood Report. PWD, Coffs Harbour, 15 pp.

Public Works Department (1983) Macksville Flood Study. The Department, Civil Engineering Division.

Public Works Department (1994) Lower Nambucca River Flood Study. Report No. NSWPW94003, February 1994, prepared by Willing and Partners for PWD, Sydney

Raine A. (1994) Use and Management of Native Vegetation for Riverbank Stabilisation and Ecological Sustainability: The Nambucca River Catchment. Report for the Department of Water Resources, NSW.

Raine, A.W. and Gardiner, J. (1995) Channel Stabilbsation Techniques and Assessment. Occasional Paper No. 03/95. Land and Water Resources Research and Development Corporation, Canberra.

Rankin, D. (1980) Trees and Rivers. Journal of the Soil Conservation Service of NSW. 7, 37-40.

Reiger, W.A. and Olive, L.J. (1988) Channel sediment loads: Comparisons and estimations. In Warner, R.F., editor, Fluvial Geomorphology of Australia. Sydney: Academic Press, 69-85.

Reinfelds, I., Rutherfurd I.D. and Bishop, P. (1995) History and Effects of Channelisation on the Latrobe River, Victoria, Australian Geographical Studies, 33(1), 60-76.

Resource Planning Pty. Ltd. (1989) Nambucca River and Missabotti Creek channel stability and gravel resources, Resource Planning: Rutherford.

Rhoads, B.L. and Herricks, E.E. (1996) Naturalisation of headwater streams in Illinois: Challenges and possibilities. In. River channel restoration: Guiding Principles for sustainable projects. Brookes, A. and Shields, F.D. (eds). Wiley, Chichester. U.K.

Riley, S.J. (1981) The relative influence of dams and secular climate change on downstream flooding, Australia. Water Resources Bulletin, 17, 361-366.

Riley, S.J. and Erskine, W.D. (1995) Human impacts on the hydrologic regime of NSW rivers. Geomorphology and river health in New South Wales. Brierley, G. and Nagel, F. (eds). Macquarie University. Conference Proceedings.p.21-30.

Ring, P.J. and Fisher, I.H. (1985) The effects of change in land use and runoff from large catchments in the upper Macintyre valley, NSW, Proc Hydrol and Water Resources Symp, Institute of Engineers Australia, 153-158.

Rolls, E. (1981): A Million Wild Acres: 200 years of man and an Australian Forest. Thomas Nelson Australia, Melbourne.

Rosgen, D.L. (1994) A classification of natural rivers. Catena, 22, 169-199.

Roy , P.R., Thom, B.G. and Wright, L.D. (1980) Holocene sequences on an embayed high energy coast: An evolutionary model. Sedimentary Geology, 26, 1-19.

Richards (1976) Channel widths and the pool and riffle sequence. Geological Society of America Bulletin, 87, 883-890.

Rutherfurd, I.D., Brooks, A.P. and Davis, I. (subm) Human influence upon erosion and sedimentation in Australian stream channels: A State of the Environment Review. Department of the Environment, Sport and Territories, Canberra.

Ryan, D.G., Ryan J.R. and Starr, B.J. (1995) The Australian Landscape: observations of explorers and early settlers. Murrumbidgee Catchment Management Committee, Wagga Wagga.

Sanderson, D.C., Bishop, P., Houston, I. and Boonsenor, M. (2001) Luminescence characterisation of quartz-rich cover sands from NE Thailand. Quaternary Science Reviews. 20, 893-900.

Schumm, S.A. (1960) The effect of sediment type on the shape and stratification of some modern fluvial deposits. American Journal of Science, 258, 177-184.

Schumm, S.A. (1969) River Metamorphosis. Journal of the Hydraulics Division (American Society of Civil Engineers), 95, 255-273.

Schumm, S.A. (1973) Geomorphic thresholds and complex response of drainage systems. In, M. Morisawa (Ed), Fluvial Geomorphology, Binghamton, Publications in Geomorphology. New York, 299-310.

Schumm, S.A. (1977) The Fluvial System. Wiley, New York.

Schumm, S.A. (1980) Some applications of the concept of geomorphic thresholds. In, Coates, V.R. and Vitek, J.D. (eds), Thresholds in Geomorphology, 473-485.

Schumm, S.A., Harvey, M.D. and Watson, C.C. (1984) Incised Channels: Morphology. Dynamics and Control. Water Resources Publication, Colarado.

Schumm, S.A. (1994) Erroneous perceptions in fluvial hazards. Geomorphology. 10, 129-138.

Schur , B. (1996) A model for funding watercourse fencing on farms. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Seal, R. and Paola, C. (1995) Observations of downstream fining on the North Fork Toutle River near Mount St. Helens, Washington. Water Resources Research. 31, 1405-1419.

Sear, D.A., Newson, M.D. and Brookes, A. (1995) Sediment-related river maintenance: the role of fluvial geomorphology. Earth Surface processes and landforms.20, 629-647.

Simon, A. (1995) Adjustment and recovery of unstable alluvial channels: Identification and approaches for engineering management. Earth Surface Processes and Landforms. 20, 611-628.

Sharma, M.L., Johnson, C.D. and Barron, R.J.W. (1982) Soil water and groundwater responses to forest clearing in a paired catchment study in south-western Australia, Proc. First Nat. Symp on Forest Hydrology, Melbourne, 11-13 May, 118-123.

Shields, F.D. and Gray, D.H. (1992) Effects of large woody vegetation on sandy levee integrity. Water Resources Bulletin, 28, 917-931.

Shields, F.D. and Gippel, C.J. (1995) Predictions of the effect of woody debris removal on flow resistance. Journal of Hydraulic Engineering, 121, 341-354.

Skull , S., Clayton, P. and Lukacs, G. (1996) Ecological investigations into streambank stabilisation practices in North Queensland. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Smith, B.W., Prescott, J.R. and Polach, H. (1992) Thermoliminescence dating of marine sediments from Spencer Gulf. In: Ambrose, W. and Duerden, P. (eds) Archaeometry: An Australian Perspective. pp282-289.

Smith, D.G. (1976) Effect of vegetation on lateral migration of an anastomosed channels of a glacial meltwater river. Geological Society of America Bulletin, 87, 857-860.

Smith, N.D., Cross, T.A., Dufficy, J.P. and and Clough, S.R. (1989) Anatomy of an avulsion. Sedimentology. 36, 1-23.

State Forests of NSW (1989) Proposed Forestry operations in the Coffs Harbour and Urunga Management Areas: Environmental and Fauna Impact Statement. State Forests of NSW Northern Region.

State Forests of NSW (1995) Coffs Harbour - Urunga Management Areas. EIS for Proposed Forestry Operations, 3 vols.

Sullivan, M.E. and Hughes, P.J. (1983) The geoarchaeology of the Sydney Basin Sandstone. In, Young, R.W. and Nanson, G.C. (eds) Aspects of Australian Sandstone Landscapes, Australian and New Zealand Geomorphology Group Special Publication, 1, 120-126.

Summerfield, M.A. (1993) Global Geomorphology, Longman Science and Technical, Essex, 537p.

Swark, W.T. and Douglass, J.E. (1974) Streamflow greatly reduced by converting deciduous hardwood stands to pine, Science, 185, 857-859.

Swift, L.W., Cunningham, G.B., and Douglas, J.E. (1988) Climate and Hydrology, in Swank and Crosby (eds) Forest Hydrology and Ecology at Coweeta, Springer-Verlag, NY, pp 33-55.

Taylor, D.W. (1948) Fundamentals of Soil Mechanics, John Wiley and Sons, New York.

Taylor, G. and Walker, P.H. (1986) Tertiary Lake Bunyon, northern Monaro, NSW. Part 1: geological setting and landscape history. Australian Journal of Earth Sciences, 33, 219-229.

Taylor, G. and Woodyer, K.D. (1978) Bank deposition in suspended load streams. In Miall, A.D., editor, Fluvial Sedimentology. Canadian Society of Petroleum Geologists Memoir, 5, 257-276.

Terzaghi, K. (1943) Theoretical Soil Mechanics, John Wiley and Sons, New York.

Thom, B.G. and Roy, P.S. (1984) Relative sea levels and coastal sedimentation in southeastern Australia in the Holocene, Journal of Sedimentary Petrology, 55, 257-264.

Thoms, M.C. (1994) Bank erosion and sand and gravel extraction in the Nambucca River and Missabotti Creek. Report to the NSW Department of Water Resources For the Nambucca TCM Committee, University of Sydney.

Thompson, D.M., Wohl, E.E. and Jarrett, R.D. (1996) A revised velocity-reversal and sediment-sorting model for a high gradient, pool-riffle stream. Physical Geography. 17, 142-156.

Thorne, C.R. (1982) Processes and Mechanisms of river bank erosion. In, Gravel Bed Rivers. Hey, R.D., Baturst, J.C. and Thorne, C.R. (eds), Chichester, 227-271.

Thorne, C.R. (1990) Effects of vegetation on river bank erosion and stability. Vegetation and Erosion. Thornes, J.B. (ed), John Wiley and Sons, 125-144.

Thorne, C.R. and Tovey, N.K. (1981) Stability of composite river banks. Earth Surface Processes and Landforms, 6, 469-484.

Thorne, C.R. and Osman, A.K. (1988) Riverbank stability analysis. II: Applications. Journal of Hydraulic Engineering, 114, 151-172.

Tooth, S. and Nanson, G.C. (1995) The geomorphology of Australia's fluvial systems: retrospect, perspect and prospect. Progress in Physical Geography. 19, 35-60.

Townsend, N. (1993) Valley of the Crooked River: History of Settlement in the Nambucca. University of NSW Press, Sydney.

Trimble, S.W. (1994) Erosional effects of cattle on streambanks in Tennessee, U.S.A. Earth Surface Processes and Landforms, 19, 451-454.

U.S. Army Corps of Engineers. Hydrologic Engineering Center. (1998) HEC RAS river analysis system. Version 2.2. Davis, CA: U.S. Army Corps of Engineers, Hydrologic Engineering Center, 3 v.

Veldkamp, A. (1991) A 3-D model of Quaternary terrace development, simulation of terrace stratigraphy and valley assymetry: A case study for the Allier Terraces, Limagne, France. Earth Surface Processes and Landforms, 14, 641-654.

Walker, J. and Reuter, D.J. (1996) Indicators of Catchment Health; A Technical Perspective. CSIRO, Melbourne, 174pp.

Walker, P.H. (1962) Terrace chronology and soil formation on the South Coast of New South Wales, Journal of Soil Science, 13, 178-187.

Walker, P.H. (1984) Terrace formation in the Illawarra region of New South Wales, Australian Geographer, 16, 141-143.

Walling, D.E. and Webb, B.W. (1983) Patterns of sediment yield. In Gregory, K.J., editor, Background in palaeohydrology: a perspective. New York: Wiley, 69-100.

Warner, R.F. (1970) Radiocarbon Dates for Some Fluvial and Colluvial Deposits in the Bellinger Valleys, New South Wales. Australian Journal of Science, 32, 368-369.

Warner, R.F. (1972) River terrace types in the coastal valleys of New South Wales. The Australian Geographer, 12, 1-22.

Warner, R.F. (1981) 'Geomorphology', In, New South Wales coastal rivers floodplain management studies: Nambucca Valley. Gutteridge, Haskins and Davey.

Warner, R.F. (1984) Man's Impact on Australian Drainage Systems. Australian Geographer, 16, 133-141.

Warner, R.F. (1987a) Spatial adjustments to temporal variations in flood regime in some Australian rivers. In Richards, K.S., editor, River channels: environment and process. Oxford: Basil Blackwell, 14-40.

Warner, R.F. (1987b) The impacts of alternating flood- and drought-dominated regimes on channel morphology at Penrith, New South Wales, Australia. IAHS Publication, 168, 327-338.

Warner, R.F. (1991) Impacts of environmental degradation on rivers, with some examples from the Hawkesbury-Nepean system. Australian Geographer, 22, 1-13.

Warner, R.F. (1992) Floodplain evolution in a New South Wales coastal valley, Australia: spatial process variations, Geomorphology, 4, 447-458.

Warner, R.F. (1995a) Human Impacts on Australian Rivers. Australian Geographical Studies, 33, 3-5.

Warner, R.F. (1995b) Predicting and managing channel change in southeastern Australia. Catena, 25, 403-418.

Warner, R.F. (1996) Do we really understand our rivers? or Rivers in the Pooh - Semper in Excreta! Australian Geographical Studies, 34, 3-17.

Warner, R.F. and Paterson, K.W. (1987) Bank erosion in the Bellinger Valley, New South Wales: definition and management. Australian Geographical Studies, 25, 3-14.

Wasson, R.J. (1998) What Should be Modelled in Large Catchments? International Symposium on Modelling Soil Erosion, Sediment Transport and Closely Related HydrologicalProcesses,Vienna, 1998. International Hydrological Programme.

Wasson, R.J., Donnely, T.H. and Murray, A.S. (1996) Imports can be dangerous-appropriate approaches to Australian rivers and catchments. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Water Conservation and Irrigation Commission (1970) River Improvement Works within the Nambucca Shire. The Commission.

Water Resources Commission (1979) River Improvements Branch - Nambucca River Investigations. The Commission.

Werrity, A. (1992) Downstream fining in a gravel bed river in southern Poland: Lithologic controls and the role of abrasion. *In*. Billi P., Hey R.D., Thorne C.R. and Tacconi D. (Eds) Dynamics of gravel bed rivers.

Wilson, C., Argent, R., Bunn, S., Davies, P., Grayson, R., Hairsine, P. and Rutherfurd, I.D. (1996) A simple model to illustrate the effects of riparian vegetation on stream values in large catchments. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Wolman, M.G. (1954) A method of sampling coarse river bed material, Transactions American Geophysical Union, 35, 951-956.

Wolman, M.G. and Leopold, L.B. (1957) River floodplains: some observation on their formation. United States Geological Survey Professional Paper 282-C, 87-107.

Woodfull, J., Rutherfurd, I. and Bishop, P. (1996) Downstream increasing flood frequency on Australian floodplains. Proceedings of the First National Conference on Stream Management in Australia. Merrijig, Cooperative Research Centre for Catchment Hydrology.

Woodyer, K.D. (1969) Bankfull frequency in in rivers. Journal of Hydrology, 6, 114-142.

Young, R.W. (1976) Radiocarbon dates from alluvium in the Illawarra District. Search, 7, 34-35.

Young, R.W. (1977) Landscape development in the Shoalhaven river catchment of southeastern New South Wales. Zeitschrift fur Geomorphologie, 21, 262-283.

Young, R.W. (1978) The study of landform evolution in the Sydney region: a review. Australian Geographer, 14, 71-93.

Young, R.W. (1983) The tempo of geomorphological change: evidence from southeastern Australia, Journal of Geology, 91, 221-230.

Young, R.W. and Nanson, G.C. (1982) Terrace formation in the Illawarra region of New South Wales. Australian Geographer, 15, 212-219.

Young, R.W. and McDougall, I. (1982) Basalts and silcretes on the coast near Ulladulla, Southern NSW. Journal of the Geological Society of Australia, 29, 425-430.

Young, R.W. and McDougall, I. (1993) Long-term landscape evolution: Miocene and modern rivers in southern New South Wales, Australia. Journal of Geology, 101, 35-49.

Young, R.W., Nanson, G.C. and Bryant, E.A. (1986) Alluvial chronology for coastal New South Wales: climatic control or random erosional events? Search. 17, 270-272.

Young, R.W., Bryant, E.A., Price, D.M., Wirth, L.M. and Pease, M. (1993) Theoretical constraints and chronological evidence of Holocene coastal development in central and southern NSW, Australia. Geomorphology, 7, 317-329.

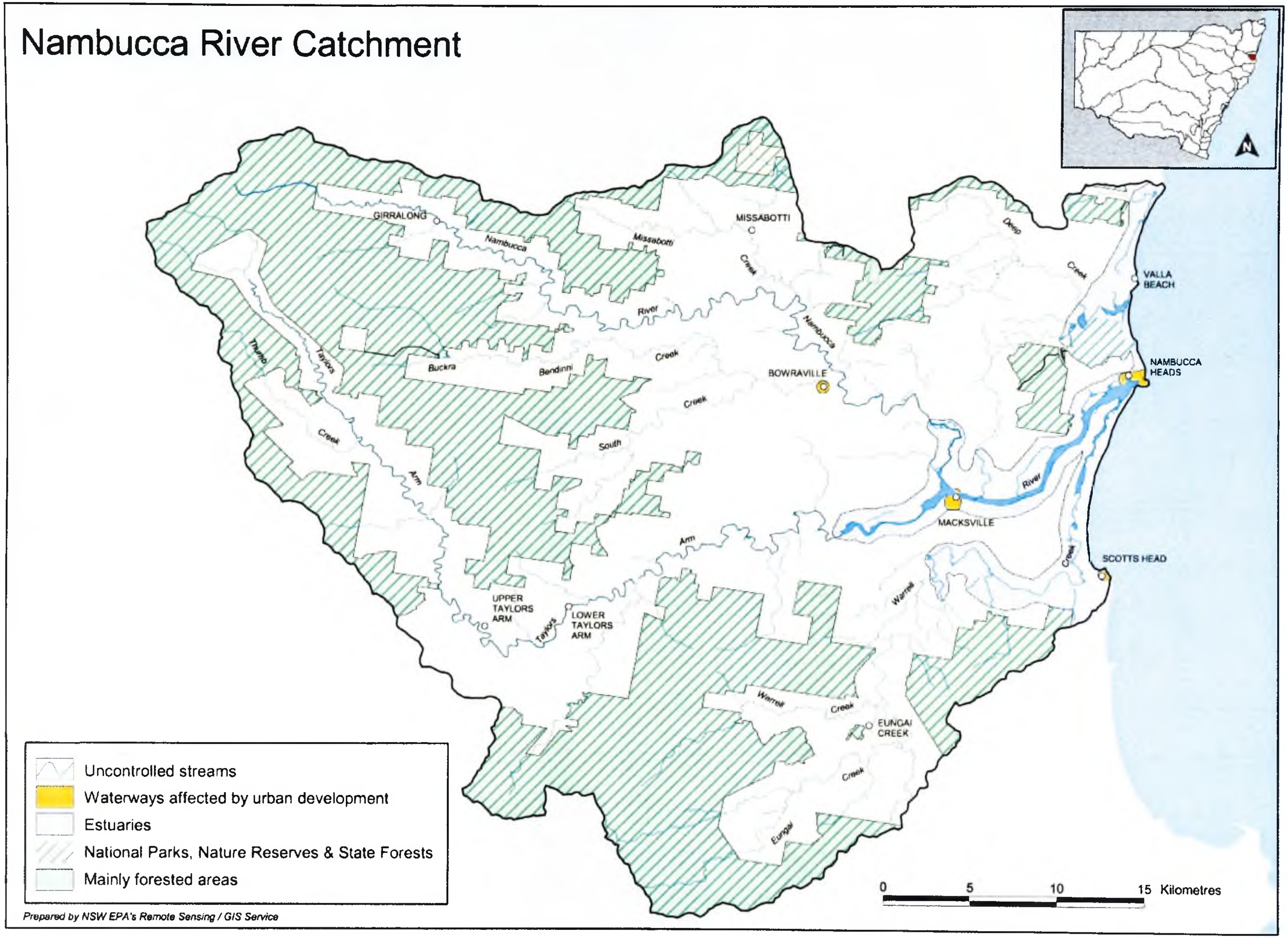
Young, R.W., Young, A.R.M., Price, D.M. and Wray, R.A.L. (2002) Geomorphology of the Namoi alluvial plain, northwestern New South Wales. Australian Journal of Earth Sciences, 49, 509-523.

Zimmerman, R.C., Goodlet, J.C. and Cromer, G.H. (1967) The influence of vegetation on channel form of small streams. Proceedings on the Symposium of River Morphology, Interscience Association of Scientific Hydrology, 75, 255-275.

APPENDICES

APPENDIX 1

NSW E.P.A . NAMBUCCA CATCHMENT MAP


Nambucca River Catchment
GIRRALONG
Nambucca
Missabotti
MISSABOTTI
Creek
Deep
Creek
VALLA BEACH
River
Nambucca
Thumb
Taylors
Buckra
Bendinni
Creek
BOWRAVILLE
NAMBUCCA HEADS
Creek
Creek
South
Arm
River
MACKSVILLE
Arm
Creek
SCOTTS HEAD
UPPER TAYLORS ARM
Taylors
LOWER TAYLORS ARM
Warrell
Warrell
Creek
EUNGAI CREEK
Creek
Eungai
Uncontrolled streams
Waterways affected by urban development
Estuaries
National Parks, Nature Reserves & State Forests
Mainly forested areas
0
5
10
15 Kilometres
Prepared by NSW EPA's Remote Sensing / GIS Service

APPENDIX 2

RESIDENT SURVEY RESULTS

Landholder Questionnaire

In July 1996, a survey was sent to residents living on stream frontage in the Nambucca catchment. The object of the survey was to canvass community opinion on the state of the channels, the history of change, the effects of different practices and, suggestions of possible solutions for the channel degradation problems. A total of 130 surveys were sent out and 51 were completed and returned. The breakdown by sub-catchment was:

Taylors Arm	17
North Arm	12
Missabotti Creek	8
South Arm	3
Buckra Bendinni Creek	6
Deep Creek	2
Warrel Creek	3
	51

The information was assessed by the study team to provide anecdotal evidence to supplement the scientific evidence obtained. From the study team's perspective it was perceived as important not only to gather collective views on stream change and causes of degradation, but to also establish what the landholders see as the main problems and possible solutions to the channel degradation problems.

The surveys revealed a myriad of conflicting views in relation to possible causes of channel degradation and suggested remedies. However, a recurring theme was dissatisfaction with the Department of Land and Water Conservation (DLWC). Most residents believed that the Department did too little in the catchment, and the small amount of work they did, or allowed to be done, lacked judgement and common sense. The lengthy bureaucratic process of referring all projects to head office has, in the eyes of the residents, allowed small problems to become large ones. Continual staff changes, delays in recruiting personnel and, an overwhelming backlog of work for the Rivercare officers has continually frustrated the residents. In addition to this, frustration was expressed in relation to the changing views and attitudes of the Department in the last decade towards tree felling, gravel extraction and methods of rehabilitation. The overall picture is that there is an overwhelming lack of faith in the government system of river management.

Despite the conflicting views of pastoralists and environmentalists within the catchment, there were some questions in the survey which returned fairly uniform responses:

- Only 14% thought that all gravel extraction was completely unnecessary
- Only 6% thought that farming practices prior to 1950 had a positive effect on the streams
- Only 2% thought farming practices since 1950 have had a positive effect on the streams
- Only 12% thought that floodplain gravel extraction was positive for the channels
- Only 6% thought Landcare has had a negative effect on the catchment
- Only 21% and 13% were against the installation of log sills and groynes, respectively
- Only 6% thought that cattle trampling was good for the streams
- Only 24% of the residents were happy with the state of the stream where they lived

Some of the more contentious issues where the percentage of supporters for and against were very even included;

- The merits of point bar gravel extraction
- The issue of casuarinas
- Views on de-snagging

A summary of the results from the survey and a selection of the replies from the residents with regards to causes and remedies of channel instability are presented in the following tables.

Below is a selection of some of the questions put to the residents and the overall results:

Results of the Landholder Questionnaire

Are you happy with the state of the channel that runs through your property?
24% YES
66% NO
10% NO COMMENT

Have any river works been carried out on your property?
64% YES
36% NO

For those who have had works, were the works successful?
59% YES
41% NO

Do you think gravel extraction is a necessary part of maintaining the channel?
53% DEFINITELY
24% YES, WITH MAJOR RESTRICTIONS
14% NO
9% UNSURE

Do you think that a lack of riparian vegetation is a major problem in need of repair?
45% YES
18% ONLY IN SOME AREAS
29% NO
8% UNSURE

Did farming practices prior to 1950 have a positive affect on the channels?
6% YES
65% NO
29% NO EFFECT/ UNSURE

Have farming practices since 1950 had a positive effect on the channels?
2% YES
60% NO
38% NO EFFECT/ UNSURE

Does cattle trampling have a positive effect on the channels?
6% YES
65% NO
29% NO EFFECT/ UNSURE

Does gravel extraction on point bars have a positive effect on the channels?
38% YES
34% NO
28% NO EFFECT/ UNSURE

Does gravel extraction within the channel have a positive effect on the channels?
25% YES
42% NO
33% NO EFFECT/ UNSURE

Does gravel extraction from the floodplains have a positive effect on the channels?
12% YES
44% NO
44% NO EFFECT/ UNSURE

Do Casuarina (or She-Oak) trees have a positive affect on the channels ?
35% YES
44% NO
21% NO EFFECT/ UNSURE

Do willow trees have a positive effect on the channels?
60% YES
27% NO
13% NO EFFECT/ UNSURE

Does the Landcare scheme have a positive effect on the channels?
65% YES
6% NO
29% NO EFFECT/ UNSURE

Do log sills have a positive effect on the channels?
48% YES
21% NO
31% NO EFFECT/ UNSURE

Do groynes have a positive effect on the channels?
52% YES
13% NO
35% NO EFFECT/ UNSURE

Does de-snagging (eg. Red Scheme in the 1970's) have a positive effect on the channels?
33% YES
40% NO
27% NO EFFECT/ UNSURE

Do present forestry practices have a positive effect on the channels?
17% YES
50% NO
33% NO EFFECT/ UNSURE

Practices with which the Landholders do not agree
(•• denotes point made in many responses)

- •• Illegal extraction by landholders
- •• Cattle in water supply
- •• Vegetation clearing on banks
- •• Too much bureaucratic bungling and 'red tape'
- •• The frustration of landholders when their initiatives are held up by DLWC paper work
- •• 'Band-aid' approaches to large 'wounds'
- •• Logging and forestry in steep upper catchment is a major problem
- •• Self funding (from gravel extraction) Landcare results in no accountability, no records, no planning and no maintenance
- •• The opinion of DLWC who believe doing nothing is best. This has lead to small problems becoming large and too expensive to fix
- •• Far too much notice is taken to people who do not make a living off the land
- •• DLWC have no respect for the landholders or their accumulated knowledge
- •• Nambucca council removing gravel from sites and not being accountable
- • Projects at present not assessed and prioritised in regard to future impacts
- • Continual DLWC staff changes
- • Belief that mass tree planting is a solution
- • Tyres in the river are flushed downstream and their chemical breakdown is extremely harmful
- • Political agendas and factions within some Landcare groups
- • Landcare is a waste of resources in the Nambucca
- • Land holders sit and wait for someone else to fix a problem that are too naive to realise that they have caused
- • Non-permitted works which; dig out swimming holes, create river crossings and remove vegetation
- • Farmers forming a Landcare group to extract gravel
- • Use of employment schemes to plant willows with no follow-up to remove them once natives begin to establish
- • River migration is our problem not degradation or bed lowering
- • Maybe nothing can be done but we shouldn't be stopped from trying
- • Battering of banks has lead to a wide shallow channel
- • Mining of the river flats should not occur whilst the channels are so unstable
- • Using tyres, concrete and excavators to instead of 'softer' options involving naturally occurring materials
- • Unskilled or uneducated operators using heavy machinery in the stream
- • Massive amounts of money wasted by Landcare planting trees unsuitable to the area such as frost intolerant rainforest species
- • The perception by some that the river is a drain
- • Irrigators who pump massive amounts of water especially in the dry season
- • Too many farmers are way behind in their thinking despite growing evidence on the effects of bank clearing and mass gravel extraction

Landholder Proposed Solutions
(•• denotes point made in many responses)

- •• Large scale below water-line extraction at all sites of previous deep pondage
- •• Attending to new sites of bank erosion immediately to stop gravel entering the system
- •• Fencing off the river from stock
- •• Use of sills, jacks and groynes as sediment traps
- •• A holistic approach to each stream rather than the piecemeal basis reliant on the co-operative landholders
- •• Clean the watercourse of unwanted vegetation and gravel
- •• Let the river turn on rock banks and not the river flats
- •• Mass planting of tree and shrubs
- •• Use gravel extraction to pay for works with the royalties going towards the maintenance of the works
- •• Cease all gravel extraction save for 'one-off' removal of gravel slugs
- •• Only practical solution is to extract gravel to pay for further restoration and vegetation control
- •• DLWC field officers should be able to give on the spot written approval for urgent preventative works such as felling undercut trees or snag removal. The current referral to head office has lead to landholders being anti the system
- •• Get rid of 95% of DLWC and bring back common sense not book educated fools
- •• All DLWC orders should be given in writing and they should pay compensation if the plan fails, just as they threaten landowners in their documents. If this were the case in the past they would owe millions
- •• Change priorities to minor problems so they do not become major. Treating the big problem areas rarely succeeds and in the meantime the smaller problems become large
- •• Use of log sills to limit stream bed lowering and brush groynes to stabilise the river
- • Battering down banks
- • Get the environmentalists and pastoralists in Bowraville to learn to live together as they do in Taylors Arm
- • Clear timber out of the river
- • Strategic removal of gravel from former deep holes in conjunction with log sills and vegetation
- • Removal of gravel islands
- • Use large rocks to halt erosion once a minor episode begins
- • A supervisor must be appointed for each sub-catchment to allow jobs to be done without such long delays
- • Education in the schools so that kids don't inherit the misguided attitudes of their parents
- • Publicity and education to dispel urban myths on the benefits of gravel extraction
- • Don't change the course of the river
- • A raising of the stream level would assist
- • Need to fix problems in the upper reaches and then work downstream
- • Remove oak trees from the banks and stop water being diverted into the banks
- • All fencing-off and revegetation should be totally funded
- • Farmers should be convinced that losing a little land to revegetation is better than losing a lot to erosion
- • Remove camphor laurel and privet
- • Forget about worrying about fish access until the chain of water holes is restored
- • Management plans should be made by well informed people from outside the catchment with no vested interests
- • No weirs or dams
- • Start at the top of the catchment with stricter controls on logging

APPENDIX 3

PHI SCALE

THE PHI (Ø) SCALE FOR SEDIMENT SIEVING

Phi Scale (Ø)	Millimetre Scale (mm)
<-7.0	126.5
-6.5	89.5
-6.0	63.4
-5.5	44.8
-5.0	31.7
-4.5	22.5
-4.0	15.9
-3.5	11.2
-3.0	7.96
-2.5	5.63
-2.0	4.00
-1.5	2.82
-1.0	2.00
-0.5	1.41
0	1.00
0.5	0.71
1.0	0.50
>1.5	<0.35

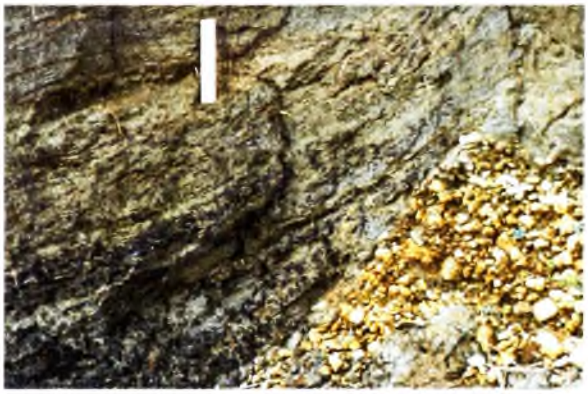
APPENDIX 4

SAMPLING METHODS PHOTOGRAPHS

Wolman Survey: Measurement of the a-, b- and c-axis of surface bed material every 0.5 m.

Sediment Sieving: Field sieving of sub-surface bed material. Sieves sizes range from 63mm to 11mm.

Terrace Drilling: Drilling into terrace sediment up to depths of 12m. Thermo-luminescence samples taken every 3m.



Radiocarbon Sampling: Organic material from exposed bank faces was collected for radiocarbon dating.

Surveying: Cross sections and long sections were surveyed at each of the 36 sites.

Thermoluminescence Sampling: Samples were taken by cleaning the exposed face & inserting a black canister.

Floodplain Auguring: Floodplains were augured to determine the nature of sediment and depth to floodplain gravels.

APPENDIX 5

GRAVEL SIZE DISTRIBUTION

Grain-size analysis

Name of the study river: ______________________

Site where grain-size sample was taken: ____________________

Sieving results:

Phi scale (ø)	Millimetre scale (*mm*)	Percentage (%)	Accumulative percentage (%)
<-7.0	126.5		
-6.5	89.5		
-6.0	63.4		
-5.5	44.8		
-5.0	31.7		
-4.5	22.5		
-4.0	15.9		
-3.5	11.2		
-3.0	7.96		
-2.5	5.63		
-2.0	4.0		
-1.5	2.82		
-1.0	2.0		
-0.5	1.41		
0	1.0		
0.5	0.71		
1.0	0.5		
>1.5	<0.35		

Note: $\phi = -3.33\log(mm)$; $mm = 10^{-\phi/3.33}$

Statistic results of grain-size analysis

Sample site		$d_{50}(ø)$	$d_m(ø)$	$\sigma_I(ø)$*	Sk_I*	K_G*
Taylors Arm:	Site 1	-5.052	-4.362	2.249	0.468	0.677
	Site 2	-4.443	-3.890	2.513	0.341	0.668
	Site 3	-3.918	-3.505	1.949	0.291	0.773
	Site 4	-3.428	-3.102	1.660	0.285	0.830
	Site 5	-2.596	-2.508	1.637	0.110	0.826
	Site 6	-3.400	-3.055	2.071	0.255	0.802
	Site 7	-2.653	-2.531	1.663	0.182	0.907
	Site 8	-3.085	-3.048	1.718	0.096	0.917
	Site 9	-3.507	-3.259	1.435	0.289	0.814
	Site 10	-2.718	-2.640	1.374	0.065	1.098
	Site 11	-3.493	-3.354	1.230	0.225	1.033
Missabotti Creek:	Site 1	-4.290	-4.117	1.718	0.177	0.911
	Site 2	-3.449	-3.280	1.726	0.136	1.101
	Site 3	-3.263	-3.148	1.662	0.130	0.881
	Site 4	-4.209	-3.972	1.137	0.350	1.018
North Arm:	Site 1	-4.695	-4.306	2.132	0.326	0.812
	Site 2	-4.116	-3.634	2.109	0.340	0.753
	Site 3	-3.760	-3.390	1.903	0.272	0.863
	Site 4	-3.308	-3.213	1.793	0.135	0.896
	Site 5	-2.640	-2.566	1.901	0.060	0.933
	Site 6	-3.063	-2.801	1.728	0.283	1.049
	Site 7	-3.040	-2.810	1.447	0.253	1.071
South Arm:	Site 1	-4.753	-4.407	1.947	0.304	0.818
	Site 2	-5.373	-5.349	0.910	0.135	1.033
	Site 3	-4.289	-3.651	2.393	0.379	0.823
	Site 4	-3.760	-3.412	1.814	0.349	0.931
	Site 5	-3.233	-3.023	1.569	0.233	1.010
Buckra Bendinni:	Site 1	-5.424	-4.876	1.770	0.483	0.728
	Site 2	-4.153	-4.062	1.387	0.139	0.885
	Site 3	-3.537	-3.338	1.814	0.212	0.928
Deep Creek:	Site 1	-2.786	-2.668	1.718	0.126	0.942
	Site 2	-2.677	-2.475	1.467	0.207	0.875
	Site 3	-3.939	-3.950	1.146	0.001	0.940
Warrel Creek:	Site 1	-2.002	-1.662	1.506	0.348	0.757
	Site 2	-2.347	-1.992	1.330	0.438	0.952
	Site 3	-2.402	-2.020	1.285	0.446	0.777

***Note:** σ_I = Inclusive Graphic Standard Deviation;
Sk_I = Inclusive Graphic Skewness;
K_G = Kurtosis.

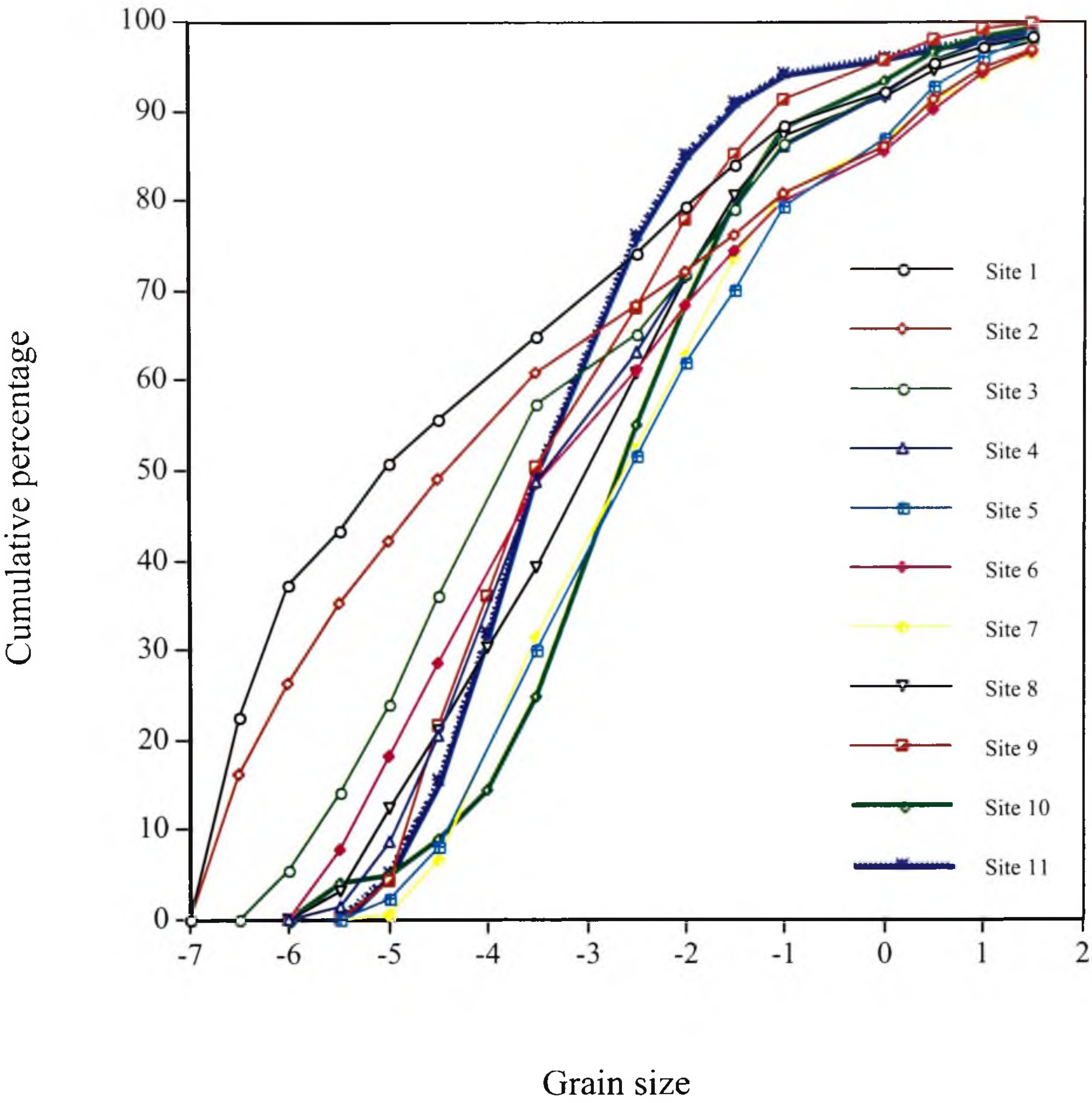


Figure 1. Grain size distribution along Taylors Arm

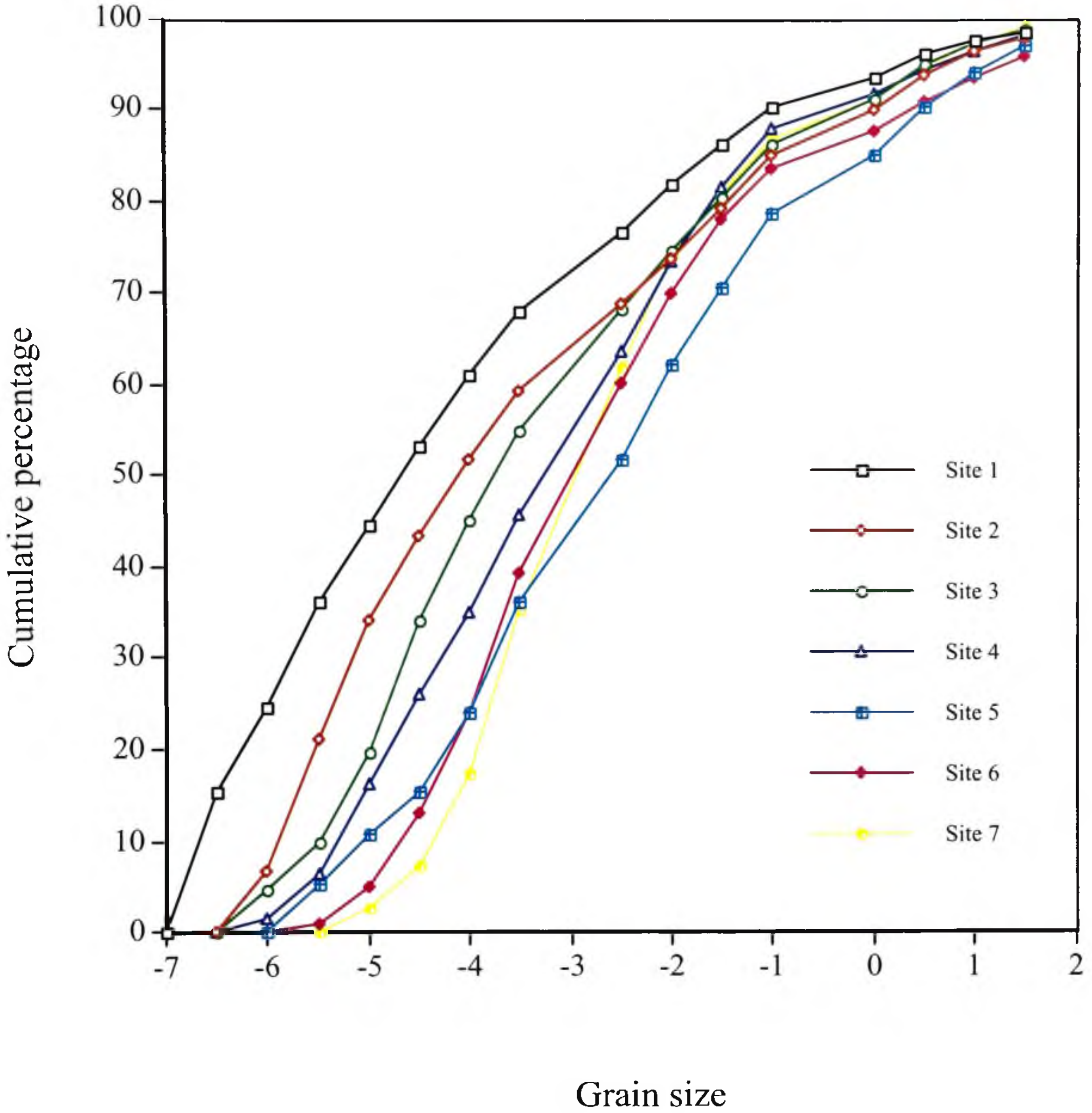


Figure 2. Grain size distribution along North Arm

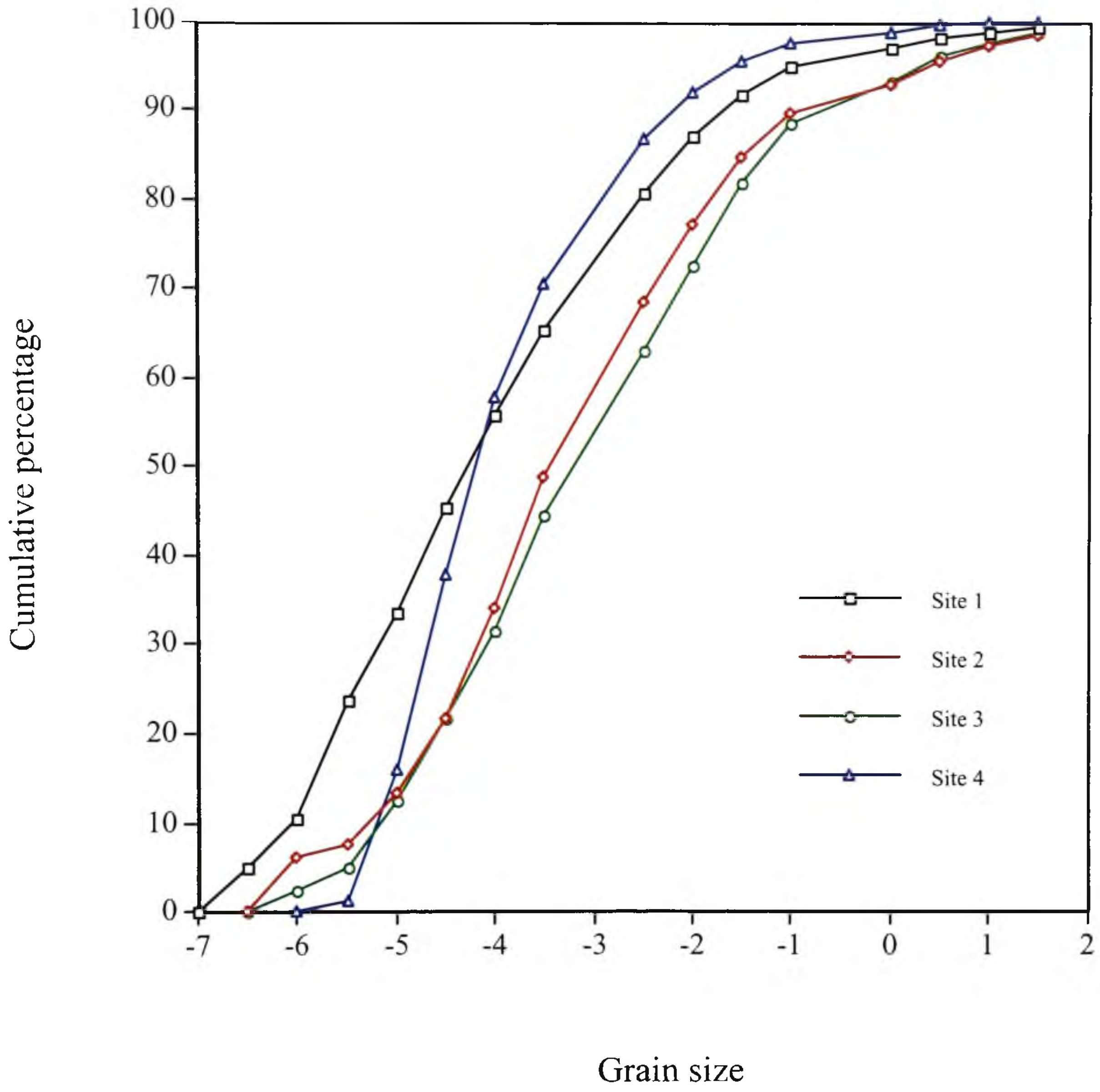


Figure 3. Grain size distribution along Missabotti Creek

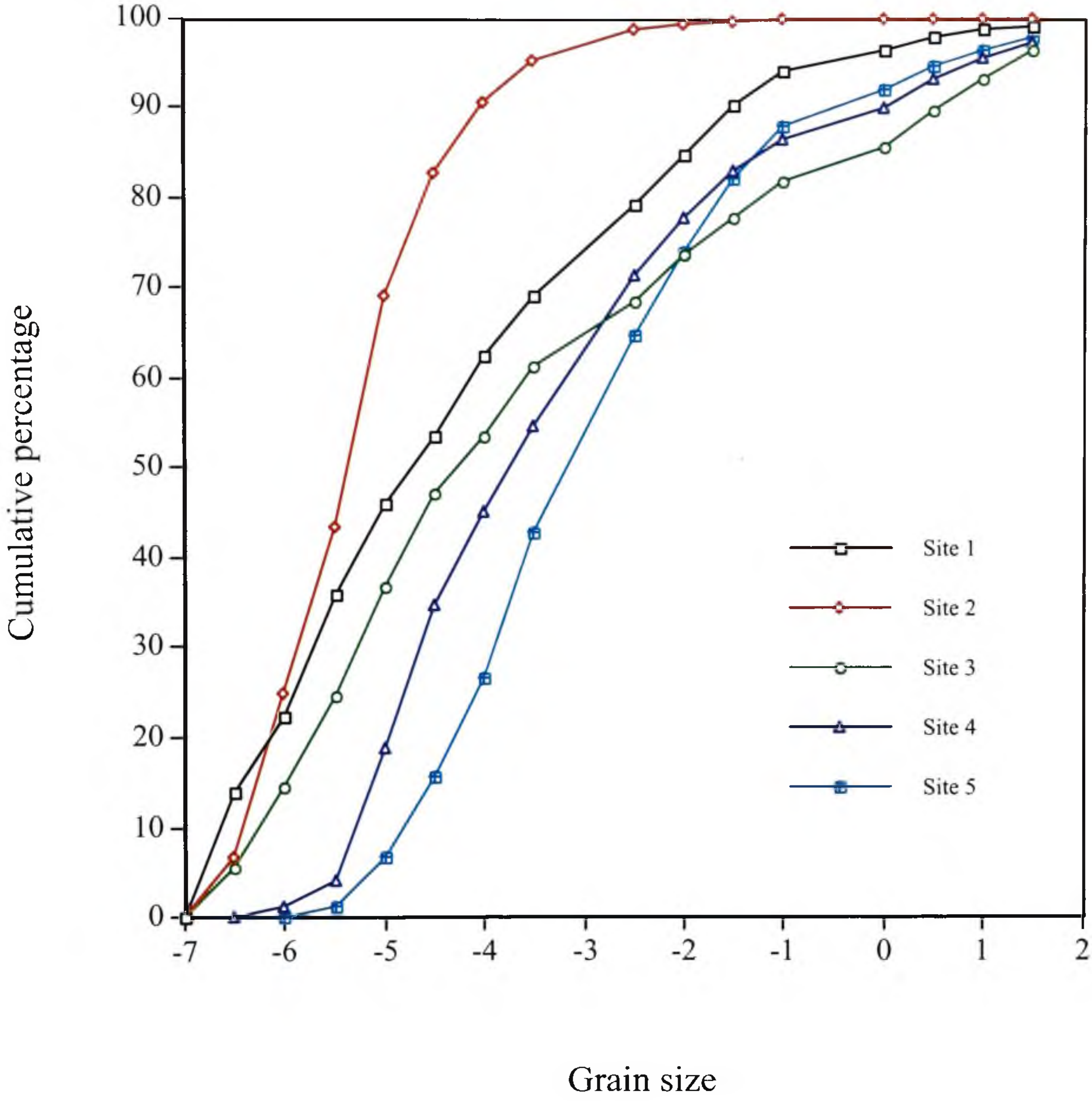


Figure 4. Grain size distribution along the South Arm

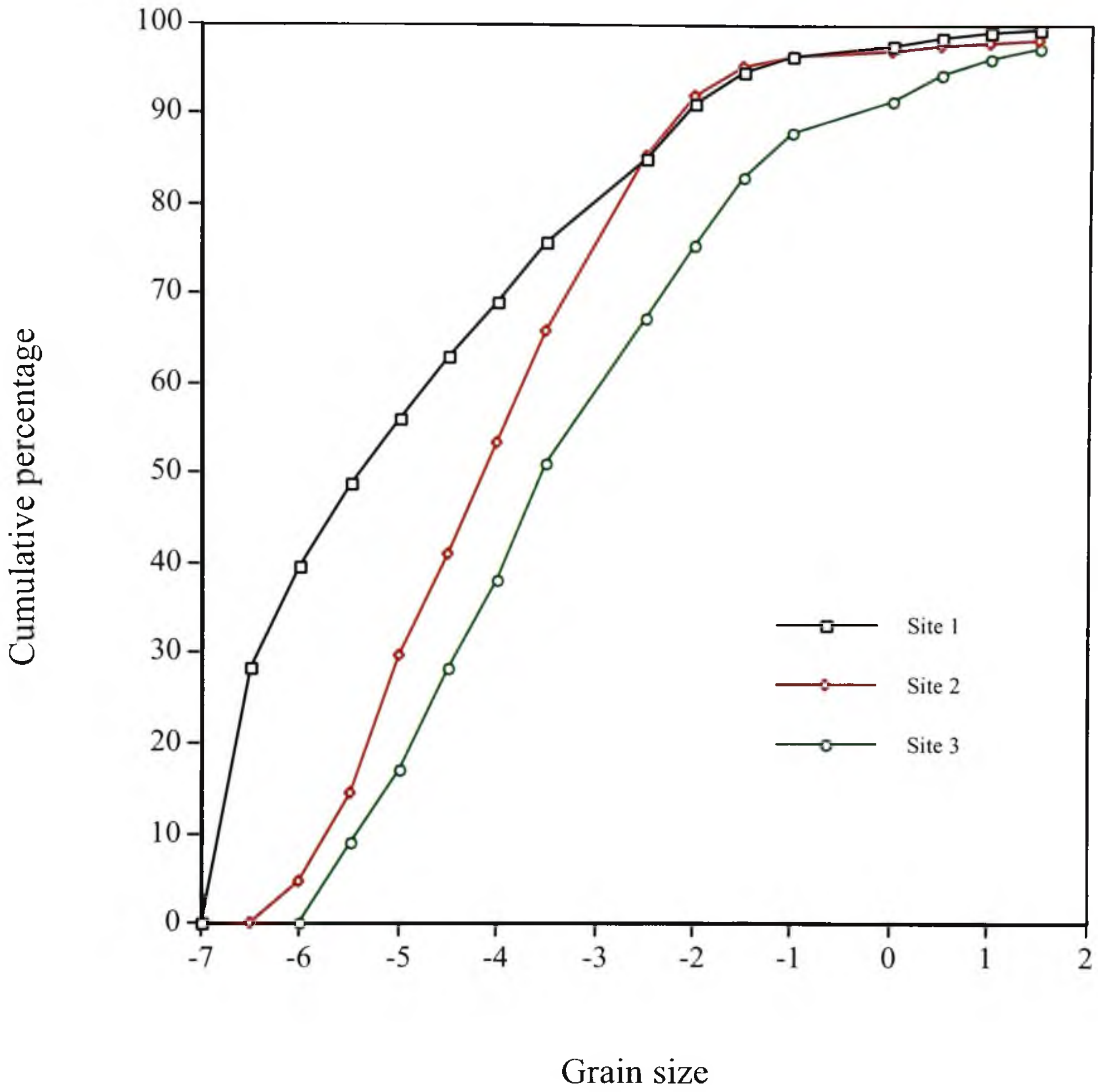


Figure 5. Grain size distribution along Buckra Bendinni Creek

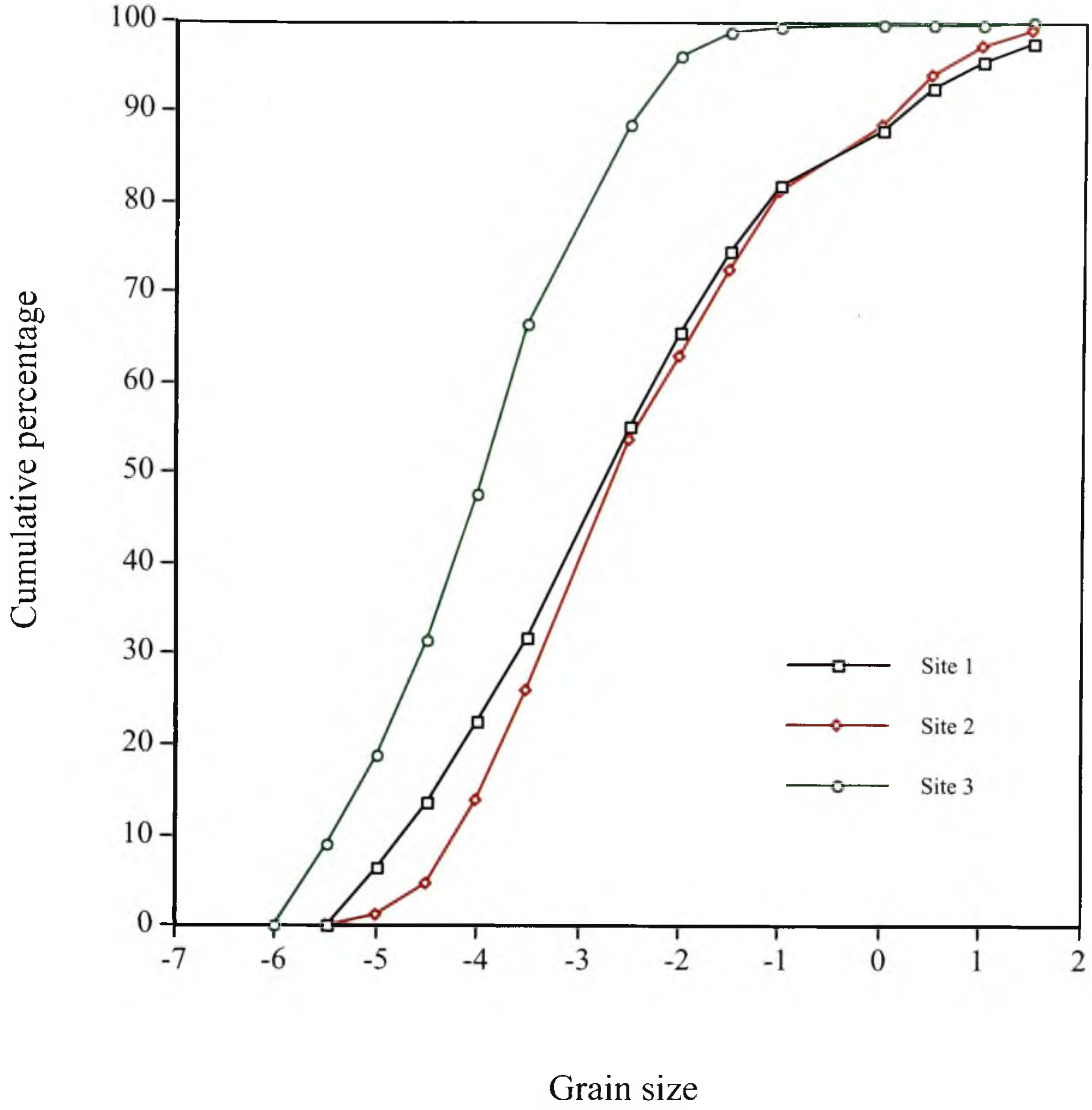


Figure 6. Grain size distribution along Deep Creek

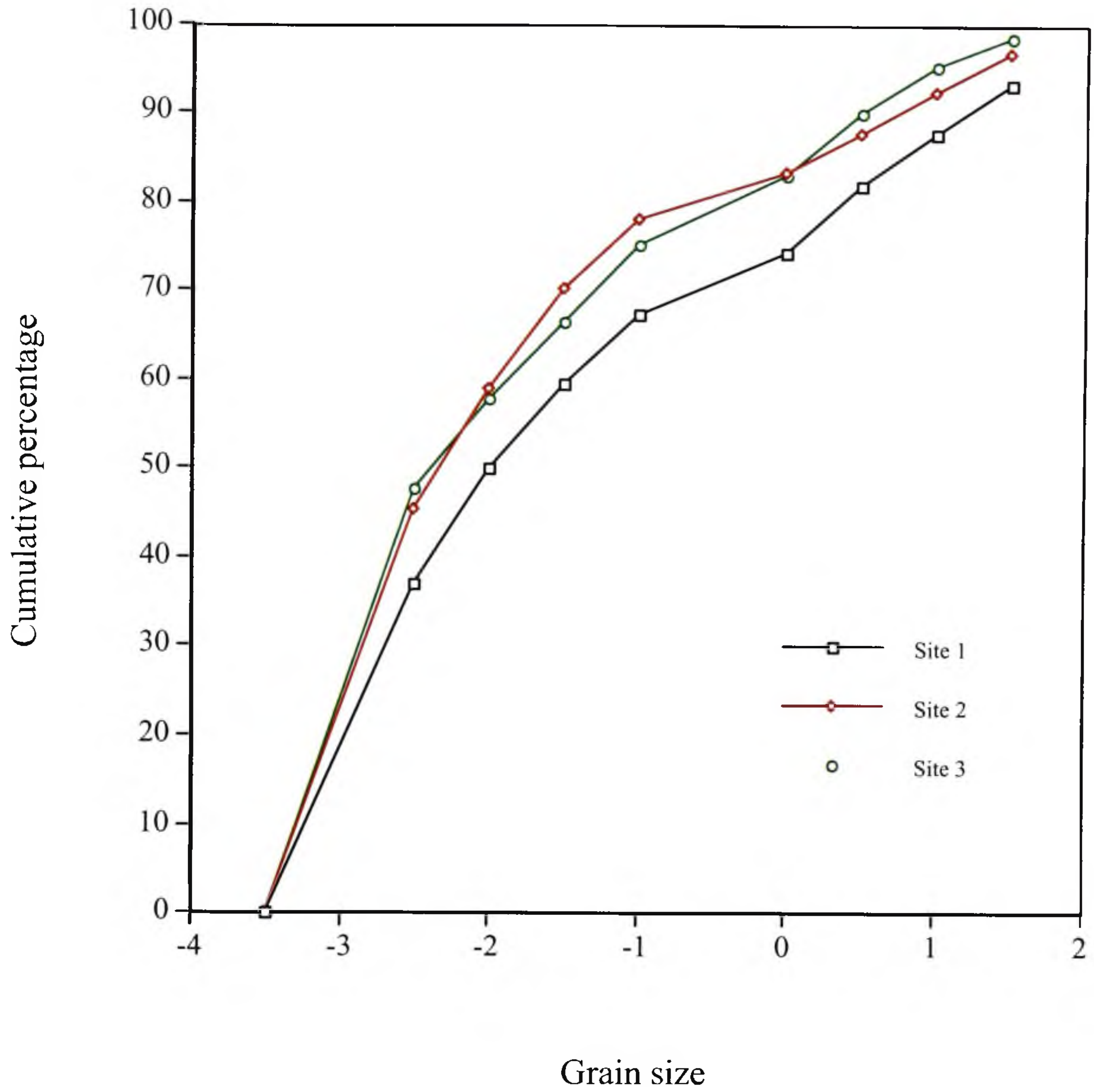
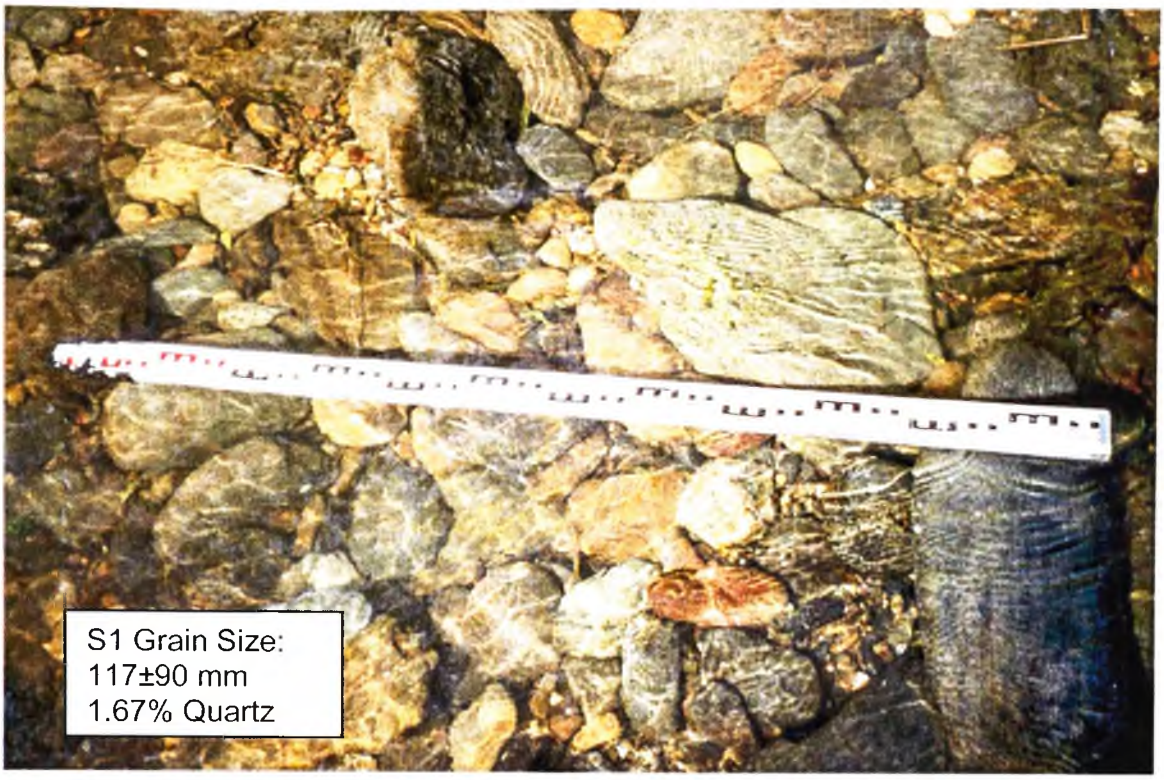
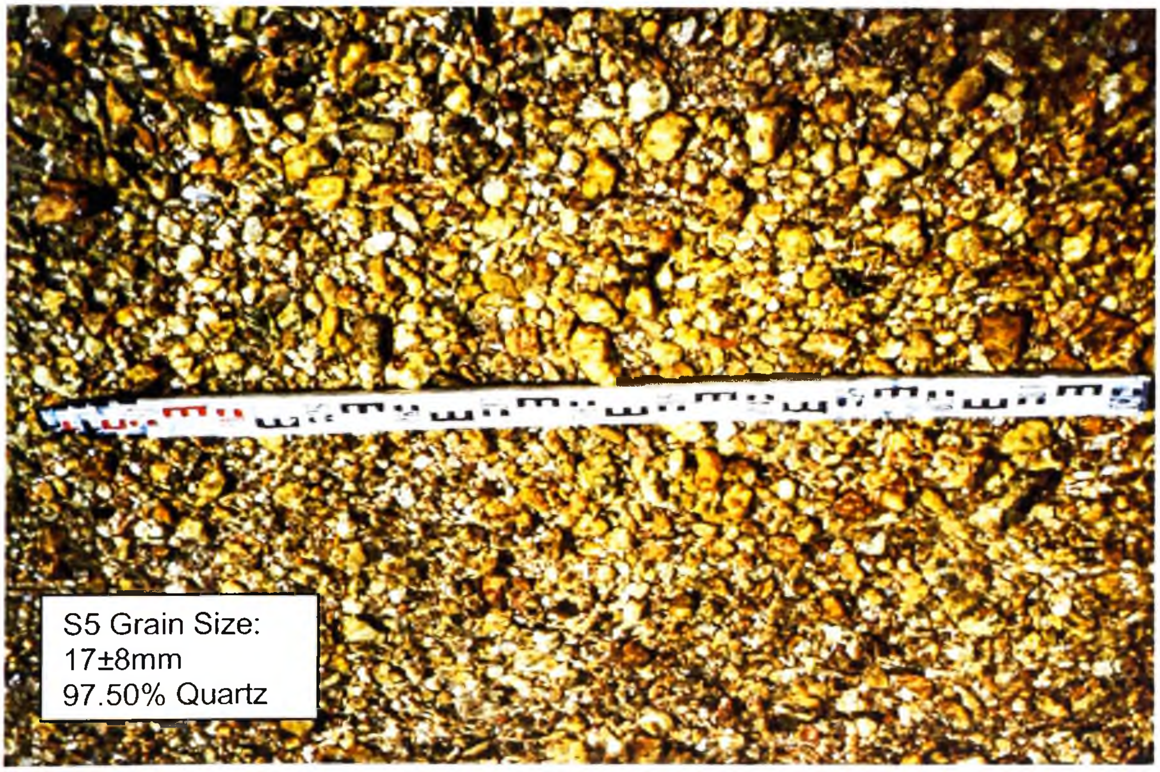


Figure 7. Grain size distribution along Warrell Creek

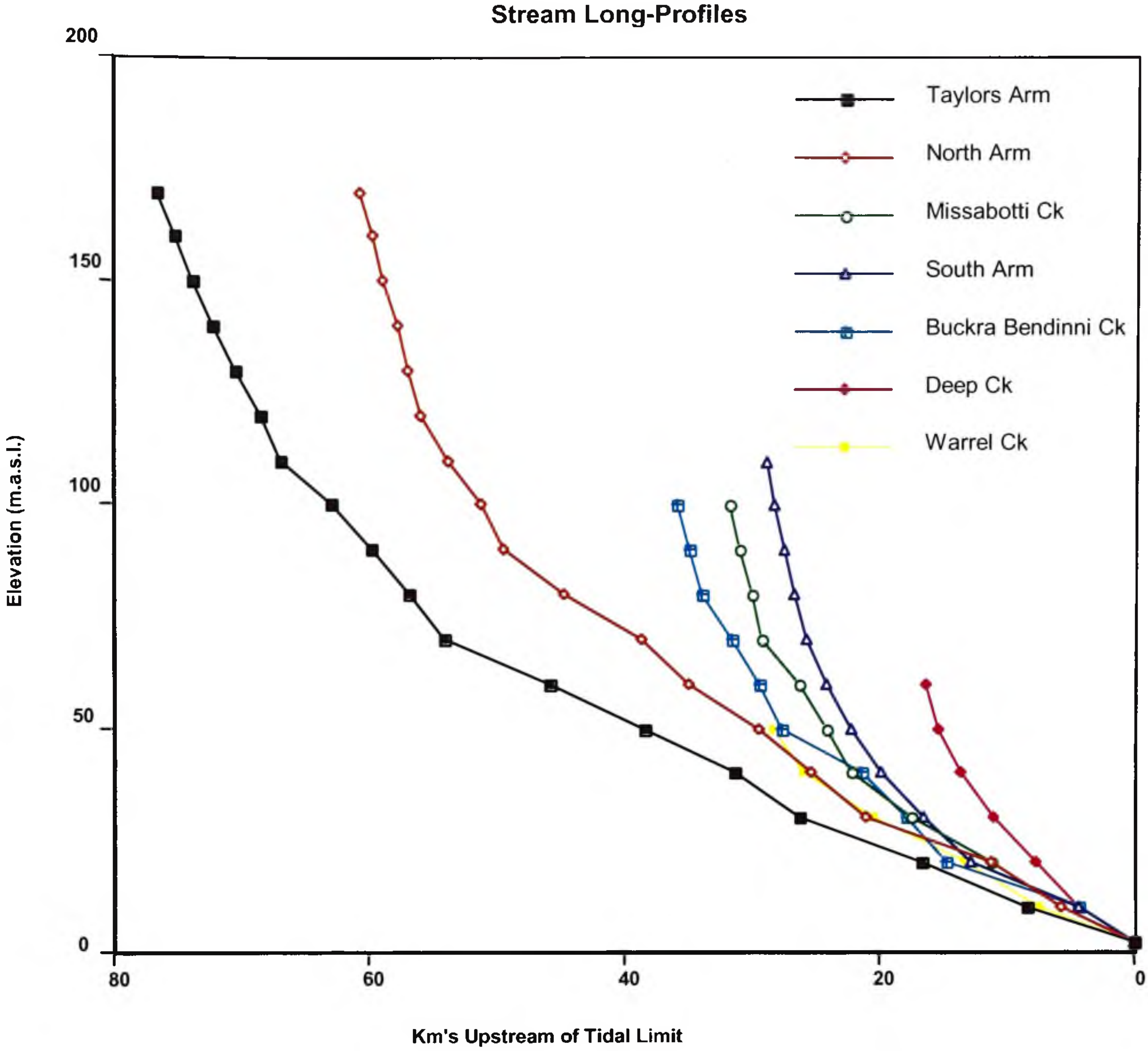


Difference in bedload size for the upper and lower reaches of the Nambucca catchment. The bed material in the above photograph is from South Arm Site 1, whilst the photograph below is at South Arm Site 5.



APPENDIX 6

STREAM LONG PROFILES



Stream Long-Profiles
Elevation (m.a.s.l.)
200
150
100
50
0
80
60
40
20
0
Km's Upstream of Tidal Limit
Taylors Arm
North Arm
Missabotti Ck
South Arm
Buckra Bendinni Ck
Deep Ck
Warrel Ck

APPENDIX 7

VALLEY UNIT DESCRIPTIONS

Valley Units and Descriptions

Taylors Arm

The uppermost unit of Taylors Arm has a catchment area of 30 km^2 at the upstream end, with the catchment area increasing to 60 km^2 at the downstream end. Here the valley floor is narrow (90-140 m) and the average slope for this reach is 0.0057. The channel is characterised by extensive low benches, an elevated floodplain and relatively little bank erosion. Dense riparian vegetation occurs on bedrock valley sides that have not been cleared, and *Casuarina cunninghamiana* commonly lines on side of the straight reaches nearest the valley side. The floodplains here most closely related to Nanson and Croke's (1992) Order A2. However, they exhibit no levees and the basal unit of gravels and boulders is thick relative to the unit of overbank fines giving them floodplain, making them similar in these respects to their Order A1 floodplains. The channel bed is highly stable and consists of large, well-imbricated phyllite clasts.

The upper-middle unit of Taylors Arm has a catchment area of 60 km^2 at the upstream end, with the catchment area increasing to 190 km^2 at the downstream end. This is the most eroded valley unit, and floodplain widths are 170-250 m, the widest anywhere on Taylors Arm. Slope, sinuosity and grain size all decrease markedly downstream of the confluence of Thumb Creek. Basal gravels and bed gravels are mostly well-rounded quartz considerably finer than upstream. The floodplains are essentially Order A2, with deposits of overbank silty sands and relatively thick basal gravels. Within-channel benches are present in places but severe erosion has removed them at most locations. The channel has become overwidened (Sites T4 and T5 in particular) which results in floodwaters being retained in the channel, even during the 100 year event.

The lower-middle unit of Taylors Arm has a catchment area of 190 km^2 at the upstream end, with the catchment area increasing to 210 km^2 at the downstream end. This is a bedrock confined valley unit (floodplain width; 135-160 m) where the channel is deep with long pools and abundant riparian vegetation (mainly *Callistemon viminalis*). The channel is stable, the bed largely unexposed even during dry periods, and floodplains (Order A2) are frequently overtopped by flooding although they are at present stable.

The lower unit of Taylors Arm has a catchment area of 210 km^2 at the upstream end, with the catchment area increasing to 380 km^2 at the downstream end. Here the

valley widths increase again but due to flanking terraces, floodplain widths are variable (120-210 m). Channel sinuosity increases to 1.52 from about 1.36 upstream and the banks are highly stable and well vegetated with *Callistemon viminalis*. Around T9 vegetation in the channel has resulted in the formation of islands which have caused some bank erosion. However, this is well contained within the zone of riparian bank vegetation. Bench formation is present at T10 where there is no vegetation, and extensive bedrock controls up and downstream of this site ensure stable reaches with long deep pools. The lower reaches of Taylors Arm are characterised by well entrenched channels.

Table A: Valley Units on Taylors Arm

Unit	Reach	Study Sites in Reach	Erosion Status
Upper Unit	Headwaters to Thumb Creek	T1 and T2	Moderately Eroded
Upper Middle Unit	Thumb Creek to Frying Pan Creek	T3, T4, T5	Severely Eroded
Lower Middle Unit	Frying Pan Creek to Taylors Arm	T6 and T7	Slightly Eroded
Lower Unit	Taylors Arm to Tidal Limit	T8, T9, T10, T11	Moderately Stable

North Arm

The upper unit of North Arm has a catchment area of 30 km^2 at the upstream end, with the catchment area increasing to 60 km^2 at the downstream end. The channel exhibits very steep gradients (0.0047) with coarse (~85 mm) bed and bank gravels predominantly schistose and phyllitic sandstone. Floodplain widths are 80-100 m and bankfull depths are 2-3m. Even in this steep reach, erosion is present with bench formation typical. The stream is moderately entrenched but less so where it moves away from bedrock.

The middle unit of North Arm has a catchment area of 60 km^2 at the upstream end, with the catchment area increasing to 160 km^2 at the downstream end. As with the middle reaches of Taylors Arm, there is a sharp decrease in slope to about 0.0018, grain size declines to ~30 mm, and there is a large increase in floodplain widths to 150-290. Sinuosity increases to 1.36. Overwidened channels and bed lowering resulting in depths of 5-8m are giving rise to very large bankfull discharges and the largest stream power values in the catchment. Vertically eroded banks and/or extensive low benches are common.

The lower unit of North Arm has a catchment area of 160 km^2 at the upstream end, with the catchment area increasing to 430 km^2 at the downstream end. Streams are

narrow and are more entrenched with depths of 6.5 to 9m and with sinuosity increasing to ~1.5, but with no change in slope. Floodplain widths are 270-380 m. Extensive stands of *Casuarina. Cunninghamiana* and camphor laurel occur on the banks along these reaches.

Table B: Valley Units on North Arm

Unit	Reach	Study Sites in Reach	Erosion Status
Upper Unit;	League Creek to Graces Creek	N1	Moderately Eroded
Middle Unit	Graces Creek to Missabotti Creek	N2, N3, N4, N5	Severely Eroded
Lower Unit	Missabotti Creek to tidal limit	N6 & N7	Moderately Eroded

Missabotti Creek

The upper unit of Missabotti Creek has a catchment area of 1 km^2 at the upstream end, with the catchment area increasing to 2.5 km^2 at the downstream end. This steep 'channel' is characterised as a series of scour pits or holes in the form of a chain of ponds and intervening sections with almost no channel. A vegetated alluvial surface obscures coarse gravels of 40-80 mm. Floodplain widths are <90 m .

The middle unit of Missabotti Creek has a catchment area of 2.5 km^2 at the upstream end, with the catchment area increasing to 40 km^2 at the downstream end. This entire reach is overwidened and gravels excavated from beneath the floodplain form an extensive gravel train with median clast sizes of 40-80 mm. Floodplain widths are from 115 to 180 m. Gradients remain steep at 0.004, sinuosity is about 1.35 and there has been extensive nickpoint retreat and bed lowering.

The lower unit of Missabotti Creek has a catchment area of 40 km^2 at the upstream end, with the catchment area increasing to 80 km^2 at the downstream end. This reach has a greater amount of overbank fines capping the floodplains than the upstream unit. Retreating nickpoints have therefore left steep vertical banks as the gravel underneath the more cohesive overbank fines is eroded. The median bed-material size is 20-40 mm. The channel slope is a much lower 0.0016 but there is little difference in sinuosity. Nickpoints and low benches encompass most of the 250-340 m valley floor. Stable sections occur where the channel abuts bedrock corners (eg. upstream of M4) and in well vegetated reaches where there is a high floodplain still present (eg. M3).

Table C: Valley Units on Missabotti Creek

Unit	Reach	Study Sites in Reach	Erosion Status
Upper Unit	Chain of Ponds above M1	Nil	Moderately Eroded
Middle Unit	Site M1 to Kennaicle Creek	M1 & M2	Severely Eroded
Lower Unit	Kennaicle Creek to North Arm	M3 & M4	Severely Eroded

South Arm

The upper unit of South Arm has a catchment area of 5 km^2 at the upstream end, with the catchment area increasing to 30 km^2 at the downstream end. There is a narrow valley with floodplain widths of 70-140 m and an essentially straight channel with a slope of 0.007 and bed-material sizes ranging 80-120 mm. Phyllitic and schistose sandstone comprise most of the bed and bank material.

The upper-middle unit of South Arm has a catchment area of 30 km^2 at the upstream end, with the catchment area increasing to 50 km^2 at the downstream end. Increased valley widths (110-210 m) and lower slopes have given the large sediment load a thin capping of fine material. Bed lowering is the cause of much of the channel erosion. Channel stability is reliant on valley side confinement with the most overwidened channels occurring where there are unstable composite banks on either side of the channel.

The lower-middle unit of South Arm has a catchment area of 50 km^2 at the upstream end, with the catchment area increasing to 80 km^2 at the downstream end. The stream has substantially changed to a narrow, sinuous channel with a few extensive pools. The floodplain is greatly confined at ~120 m. Quartz is the dominant bed material (median size of 37mm) and is present in the floodplain profile not as a massive deposit but mixed with sand and silt. Streams are well vegetated by comparison with those elsewhere, with the banks appearing to be much more stable.

The lower unit of South Arm has a catchment area of 80 km^2 at the upstream end, with the catchment area increasing to 180 km^2 at the downstream end. Incision has lead to a well-entrenched channel. Pre-1942 cut-offs have lowered sinuosity and channel expansion and bench formation have resulted. The floodplain width is 150-250 m. The gradient is low (0.0012) as the bed material size is reduced (median <20 mm; mostly quartz). Some large gravel deposits appear once more at S5.

Table D: Valley Units on South Arm

Unit	Reach	Study Sites in Reach	Erosion Status
Upper Unit	Headwaters to S2	S1 & S2	Slightly Eroded
Upper Middle Unit	S2 to Ketelghay	S3	Severely Eroded
Lower Middle Unit	Ketelghay to Buckra Bendinni Creek	S4	Slightly Eroded
Lower Unit	Buckra Bendinni Creek to tidal limit	S5	Moderately Eroded

Buckra Bendinni Creek

The upper unit of Buckra Bendinni Creek has a catchment area of 20 km^2 at the upstream end, with the catchment area increasing to 40 km^2 at the downstream end. Channel gradient is 0.0047 and the median bed material size is 120 mm (10% quartz). The very wide and straight channel has a sinuosity of only 1.10. The valley floor is unusually wide for an upper reach; ~180 m. Bankfull width is high and the depth low.

The middle unit of Buckra Bendinni Creek has a catchment area of 40 km^2 at the upstream end, with the catchment area increasing to 60 km^2 at the downstream end. Channel and floodplain widths remain similar to those upstream. However, there is a larger amount of overbank fines and more readily transportable bed material with a median size of 40 mm (50% quartz). Sinuosity is 1.16.

The lower unit of Buckra Bendinni Creek has a catchment area of 60 km^2 at the upstream end, with the catchment area increasing to 90 km^2 at the downstream end. Slope decreases to 0.001 and bed material median size to 28mm (70% quartz). Bank profiles reveal a mixed deposition of gravel, sand and silt (similar to that in the lower middle unit of South Arm). The valley is the same width as upstream. There are higher floodplains and a more sinuous channel (sinuosity is 1.25).

Table E: Valley Units on Buckra Bendinni Creek

Unit	Reach	Study Sites in Reach	Erosion Status
Upper Unit	Little Wonder Creek to Travellers Creek	B1	Moderately Eroded
Middle Unit	Travellers Creek to Argents Hill	B2	Severely Eroded
Lower Unit	Argents Hill to South Arm	B3	Slightly Eroded

Deep Creek

The upper and middle units of Deep Creek has a catchment area of 4 km^2 at the upstream end, with the catchment area increasing to 30 km^2 at the downstream end. The channel is entrenched and stable with a slope of 0.0036. There are a series of concrete weirs along the length of this unit and the valley floor is only 50-80 m wide with no gravel evident in the floodplain despite 15 mm quartz in the gravel bed. There is no evidence of erosion on the well-vegetated and cohesive banks.

The lower unit of Deep Creek has a catchment area of 30 km^2 at the upstream end, with the catchment area increasing to 55 km^2 at the downstream end. A narrow channel exists with a small contemporary floodplain up to 120 m in width, containing some gravel deposits. Extensive terraces are evident. Erosion is occurring in the lower reaches where the basal gravel units in the terraces have been exposed and eroded as a result of bed lowering.

Table F: Valley Units on Deep Creek

Unit	Reach	Study Sites in Reach	Erosion Status
Upper and Middle Unit	Headwaters to Viewmont Creek	D1 & D2	Highly Stable
Lower Unit	Viewmont Creek to Tidal Limit	D3	Moderately Eroded

Warrell Creek

The upper and middle units of Warrell Creek has a catchment area of 3 km^2 at the upstream end, with the catchment area increasing to 100 km^2 at the downstream end. This reach displays a stable, entrenched system with a silt/clay floodplain, riparian vegetation and no evidence of gravel deposits away from the channel, or lateral erosion. Quartz bedload is ~11mm with a low slope of 0.0017 and high Manning's n values from channel vegetation and woody debris. Bankfull depth is high but floodplain width is only 70-110 m.

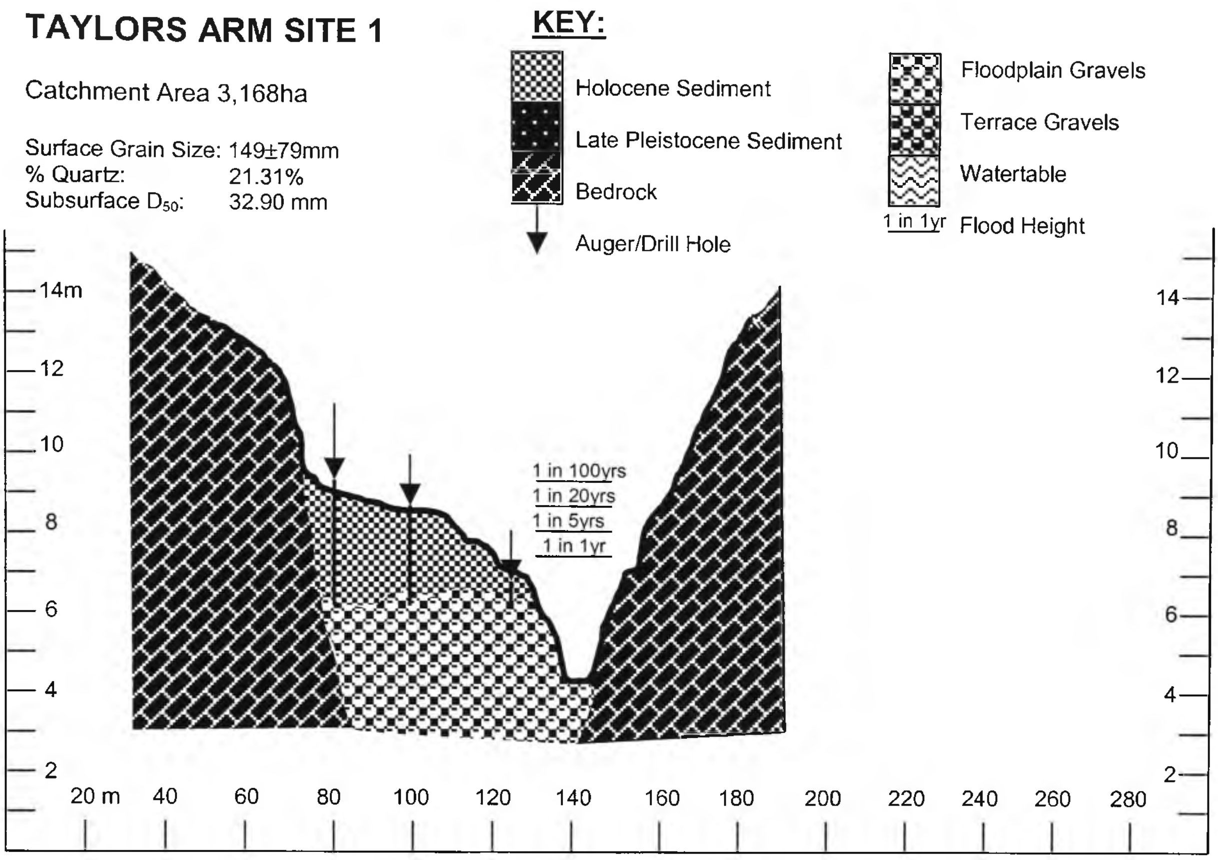
The lower unit of Warrell Creek has a catchment area of 100 km^2 at the upstream end, with the catchment area increasing to 190 km^2 at the downstream end. Terraces are evident and the silt/clay floodplains are 150-250 m wide. The channel widens only where riparian vegetation has been removed, and there is no evidence of recent lateral channel movement. Channels sinuosity is 1.54 and there is a slope of 0.0014. The stream banks are cohesive and well vegetated. The quartz bed material has a median size of 14mm.

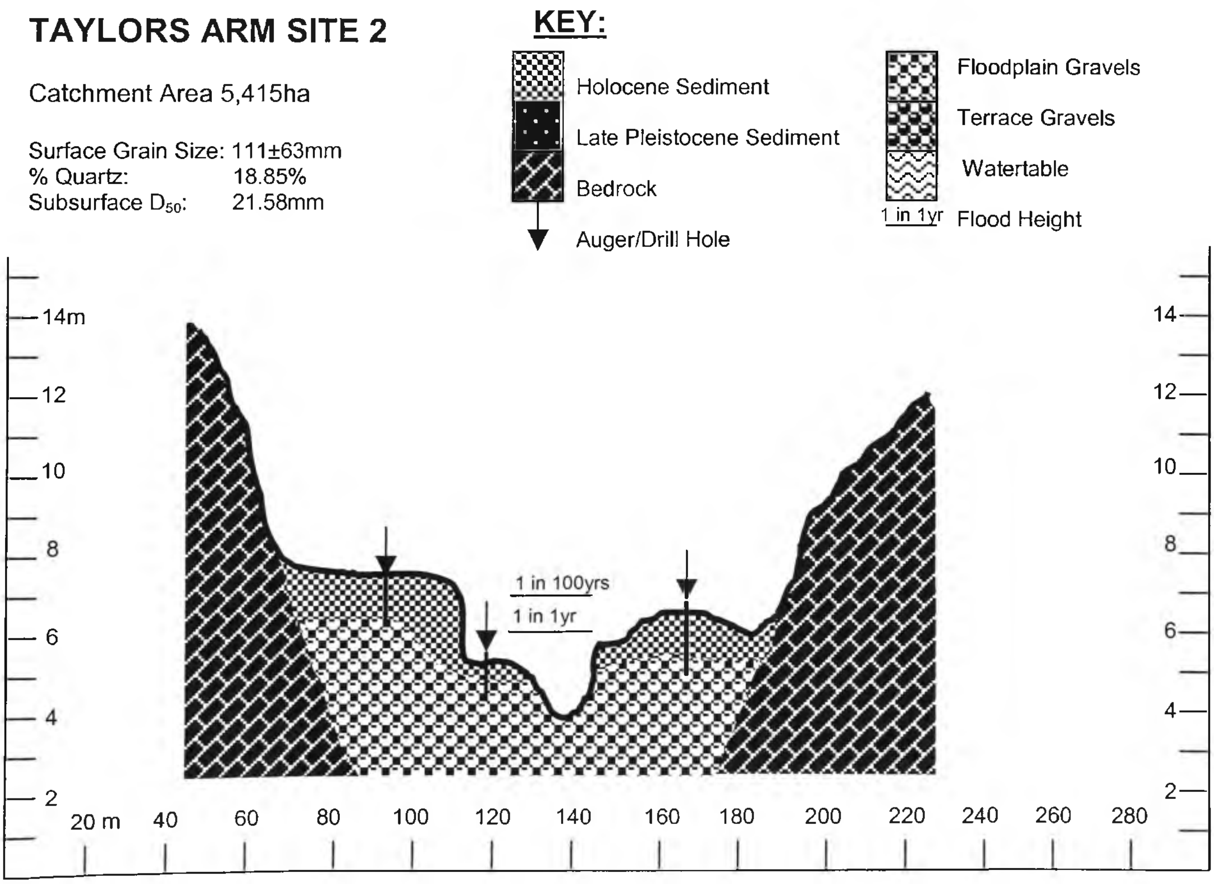
Table G: Valley Units in Warrell Creek

Unit	Reach	Study Sites in Reach	Erosion Status
Upper and Middle Unit	Eungai Creek	W1 & W2	Highly Stable
Lower Unit	Allgomera Creek to tidal limit	W3	Moderately Stable

APPENDIX 8

STUDY SITES CROSS-SECTIONS AND FLOODPLAIN STRATIGRAPHY


TAYLORS ARM SITE 1
Catchment Area 3,168ha
Surface Grain Size: 149±79mm
% Quartz: 21.31%
Subsurface D50: 32.90 mm
KEY:
Holocene Sediment
Late Pleistocene Sediment
Bedrock
Auger/Drill Hole
Floodplain Gravels
Terrace Gravels
Watertable
1 in 1yr Flood Height
14m
12
10
8
6
4
2
1 in 100yrs
1 in 20yrs
1 in 5yrs
1 in 1yr
20 m
40
60
80
100
120
140
160
180
200
220
240
260
280


TAYLORS ARM SITE 2
Catchment Area 5,415ha
Surface Grain Size: 111±63mm
% Quartz: 18.85%
Subsurface D50: 21.58mm
KEY:
Holocene Sediment
Late Pleistocene Sediment
Bedrock
Auger/Drill Hole
Floodplain Gravels
Terrace Gravels
Watertable
1 in 1yr Flood Height
14m
12
10
8
6
4
2
1 in 100yrs
1 in 1yr
20 m
40
60
80
100
120
140
160
180
200
220
240
260
280

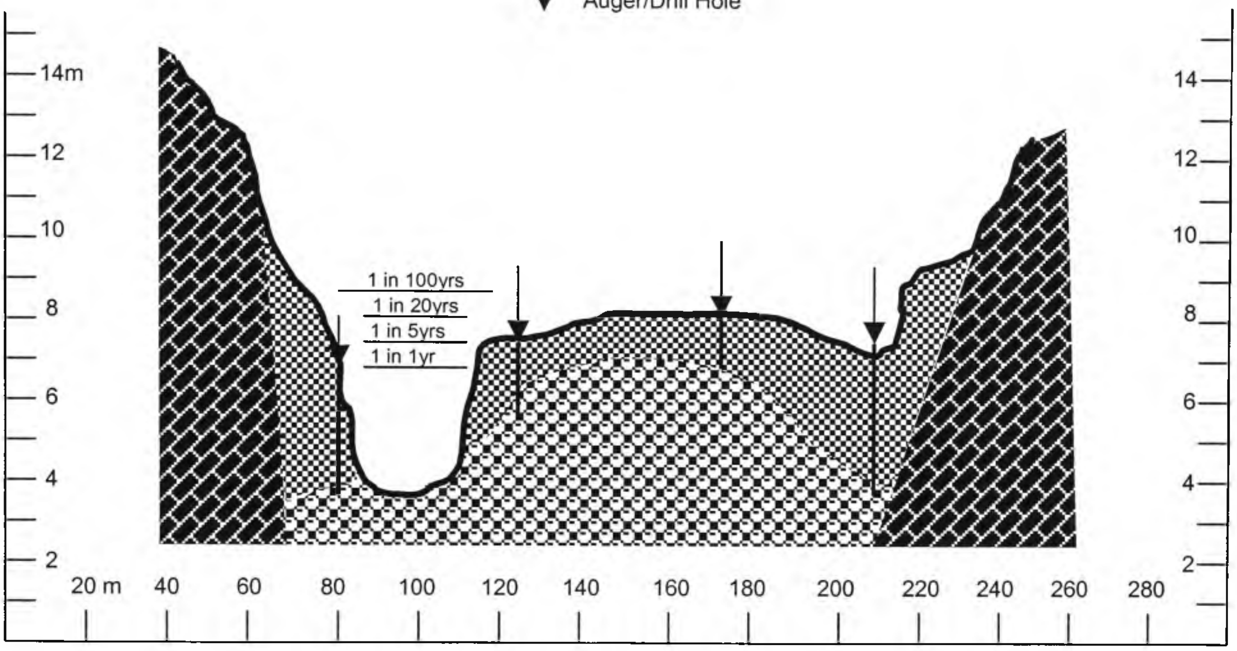
TAYLORS ARM SITE 3

Catchment Area 11,919ha

Surface Grain Size: 40±23mm
% Quartz: 50.82%
Subsurface D_{50}: 15.01mm

KEY:

- Holocene Sediment
- Late Pleistocene Sediment
- Bedrock
- Auger/Drill Hole
- Floodplain Gravels
- Terrace Gravels
- Watertable
- 1 in 1yr Flood Height



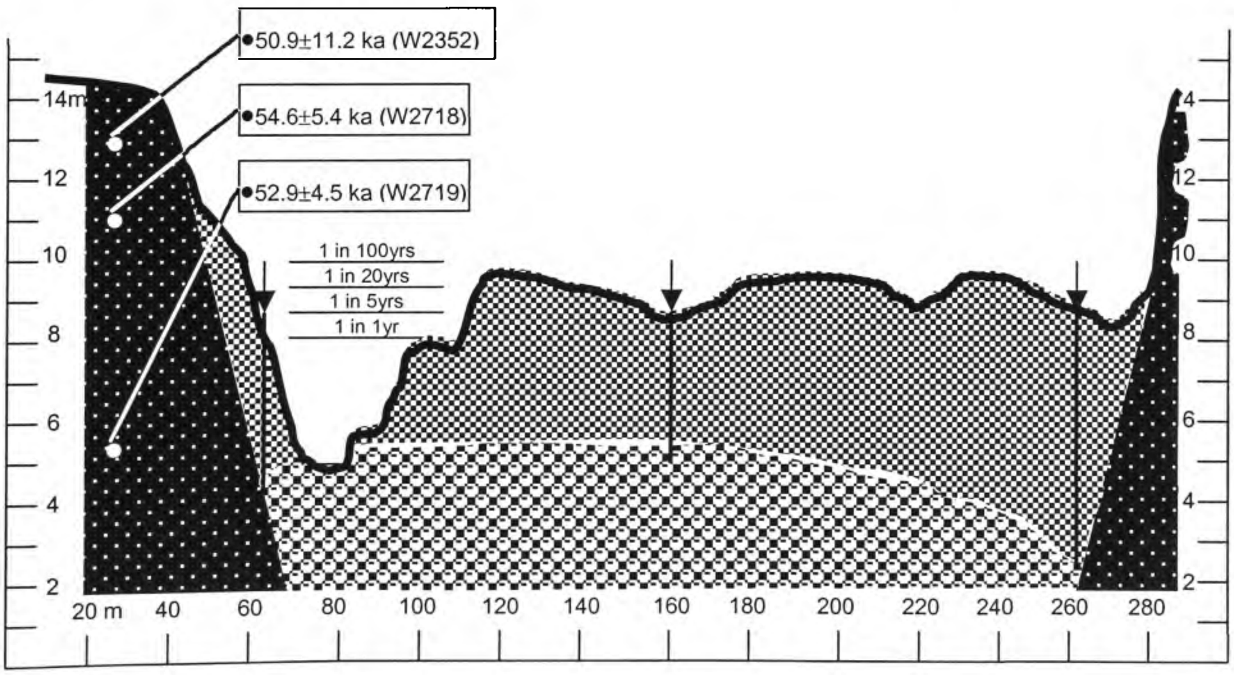
TAYLORS ARM SITE 4

Catchment Area 15,845ha

Surface Grain Size: 30±16mm
% Quartz: 50.82%
Subsurface D_{50}: 10.70 mm

KEY:

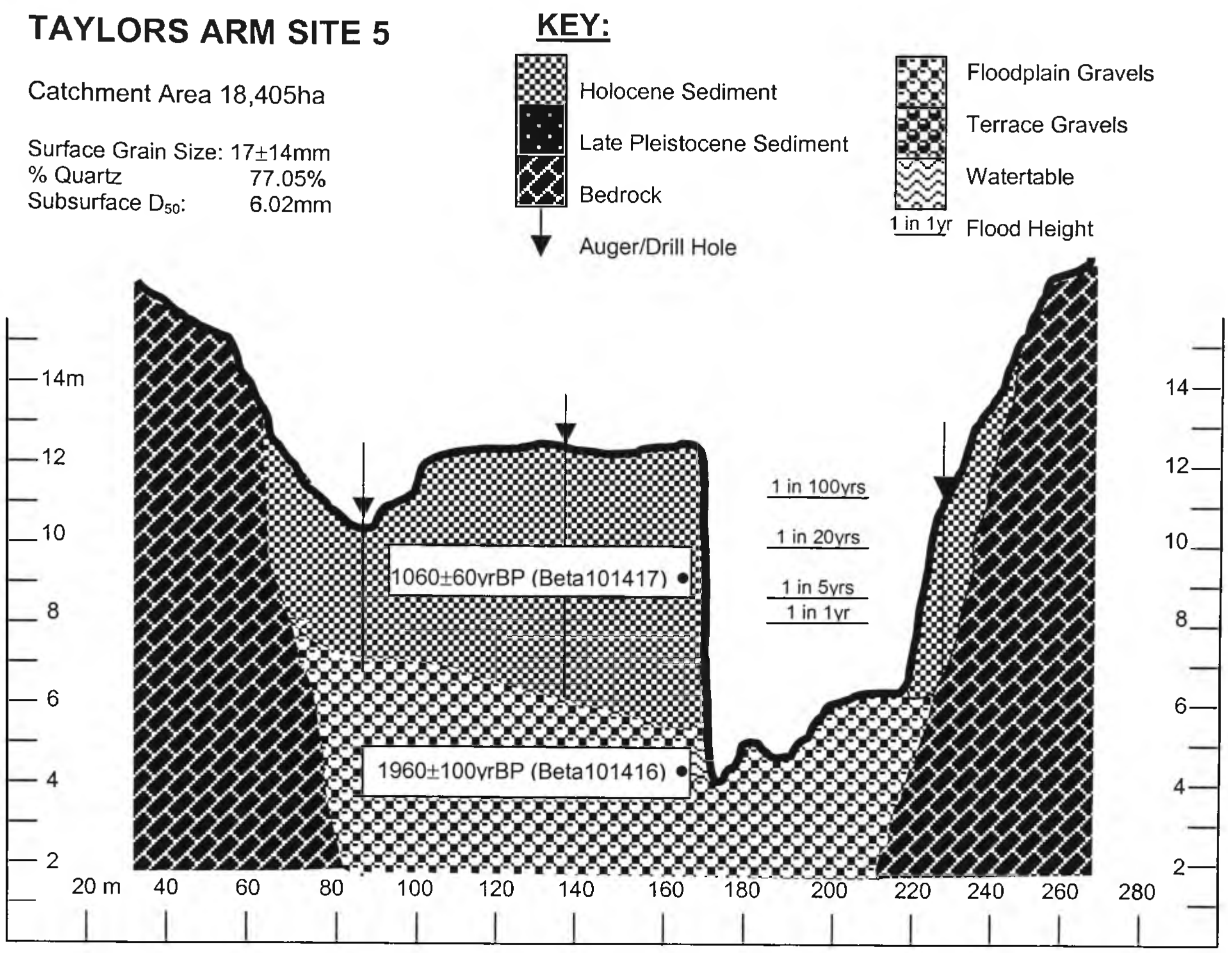
- Holocene Sediment
- Late Pleistocene Sediment
- Bedrock
- Auger/Drill Hole
- Floodplain Gravels
- Terrace Gravels
- Watertable
- 1 in 1yr Flood Height



TAYLORS ARM SITE 5

Catchment Area 18,405ha

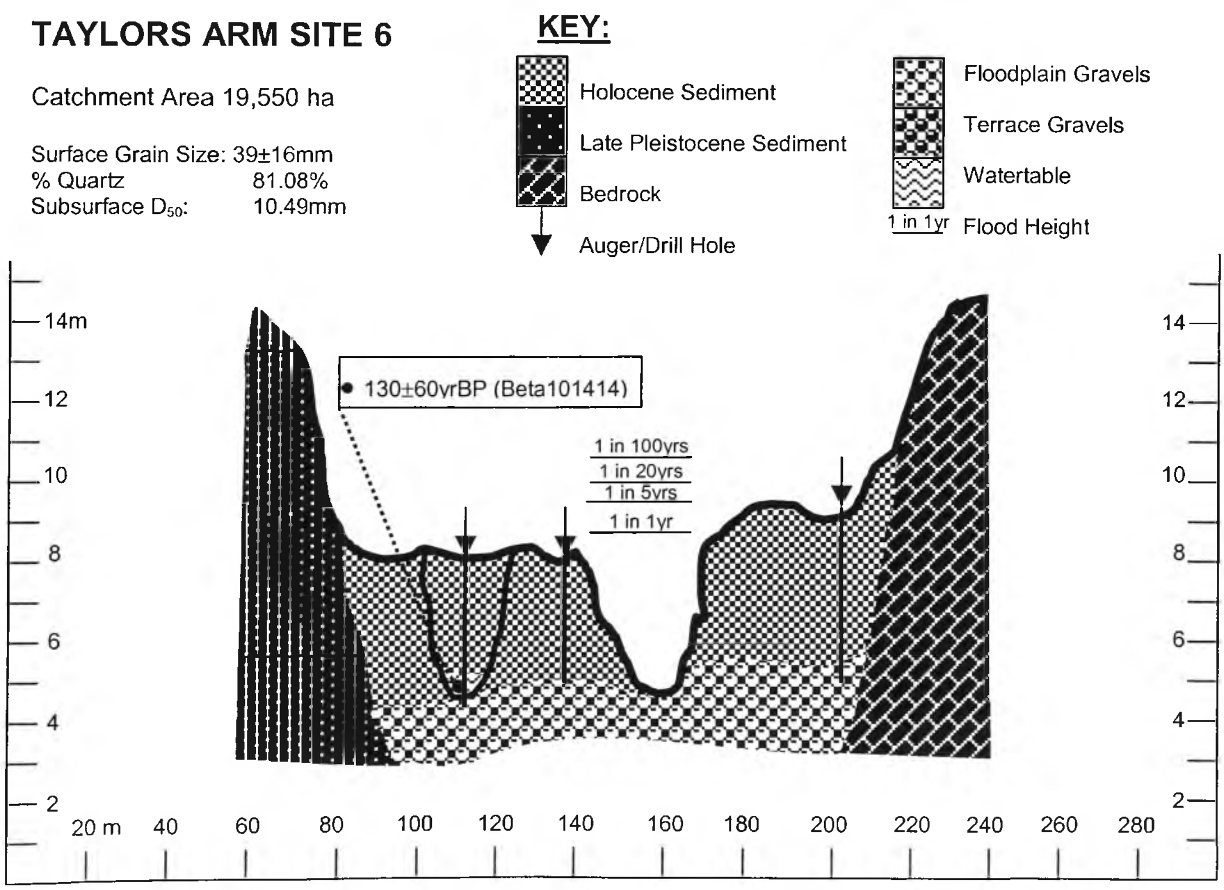
Surface Grain Size: 17±14mm
% Quartz 77.05%
Subsurface D_{50}: 6.02mm



TAYLORS ARM SITE 6

Catchment Area 19,550 ha

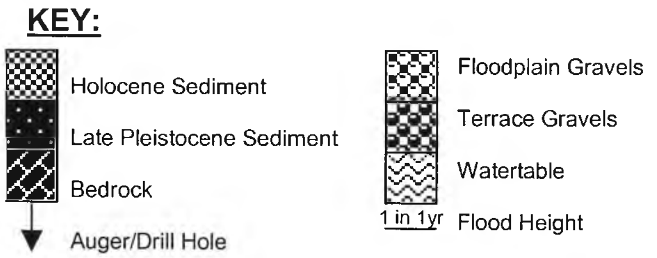
Surface Grain Size: 39±16mm
% Quartz 81.08%
Subsurface D_{50}: 10.49mm

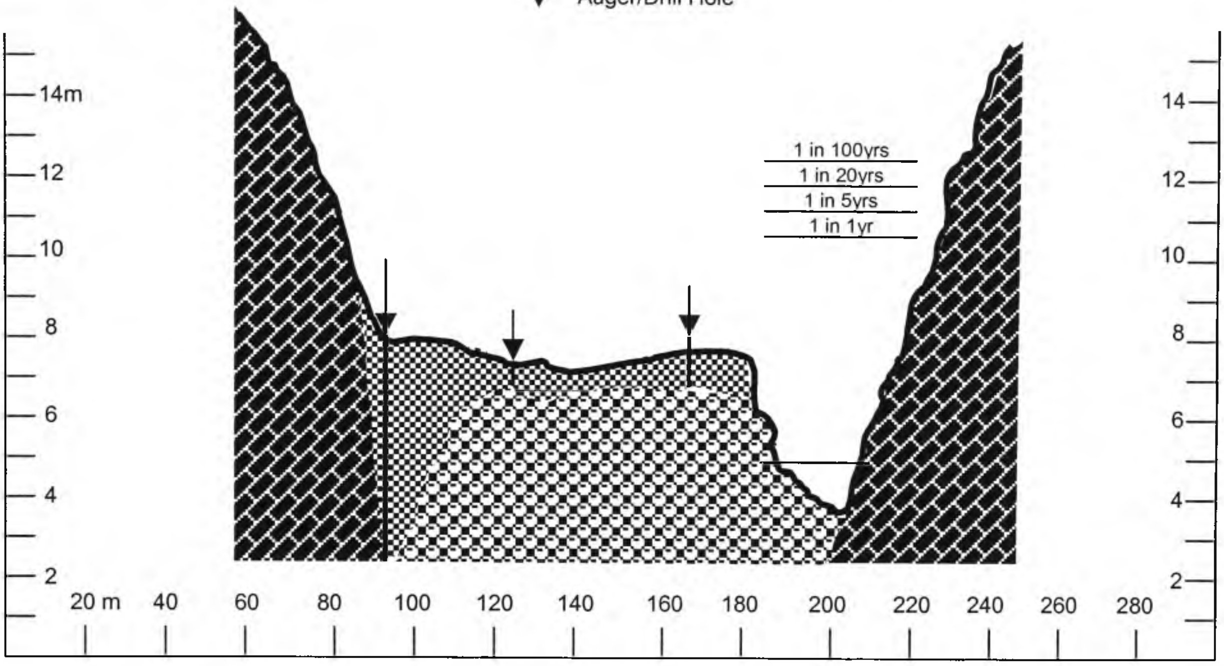


TAYLORS ARM SITE 7

Catchment Area 20,120 ha

Surface Grain Size: 17±7mm
% Quartz: 77.66%
Subsurface D_{50}: 6.26mm

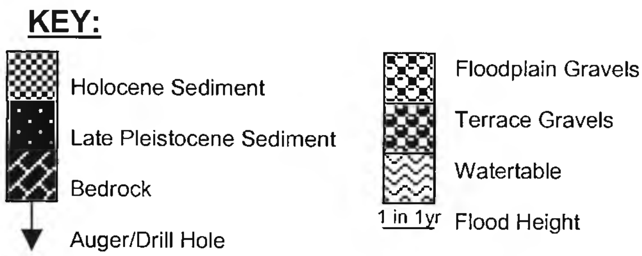


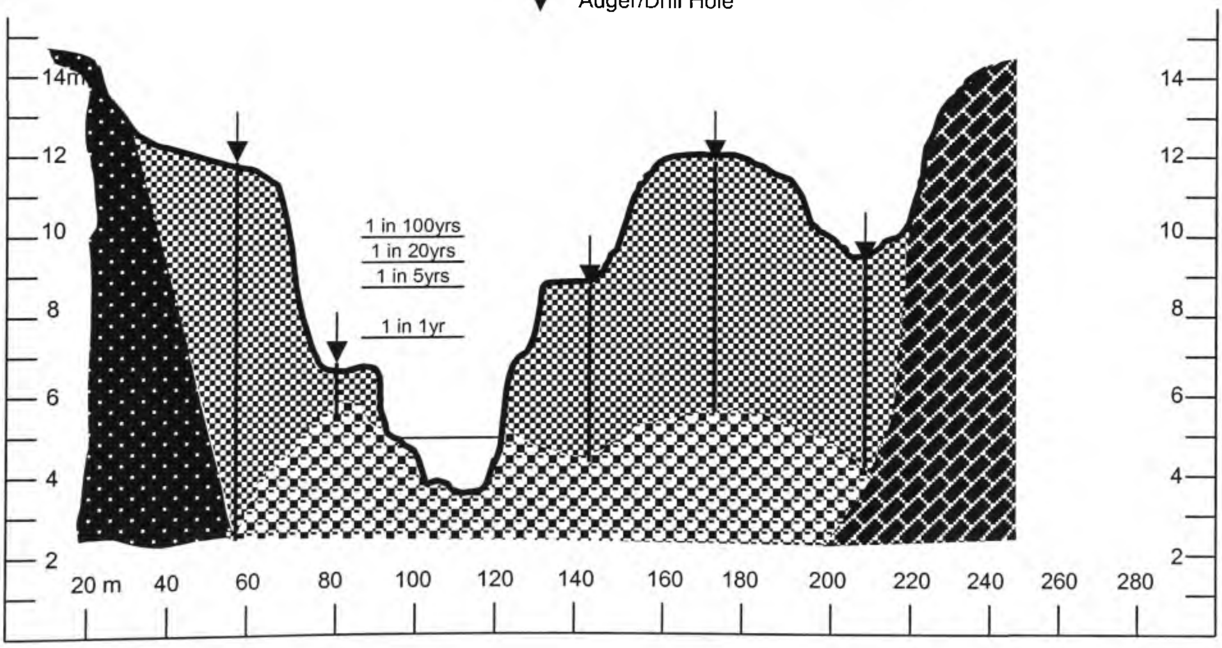


TAYLORS ARM SITE 8

Catchment Area 21,430 ha

Surface Grain Size: 39±16mm
% Quartz: 81.08%
Subsurface D_{50}: 8.44mm

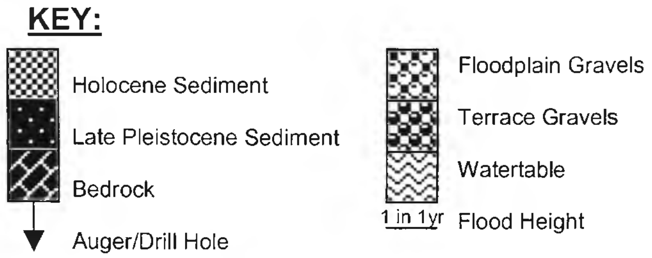


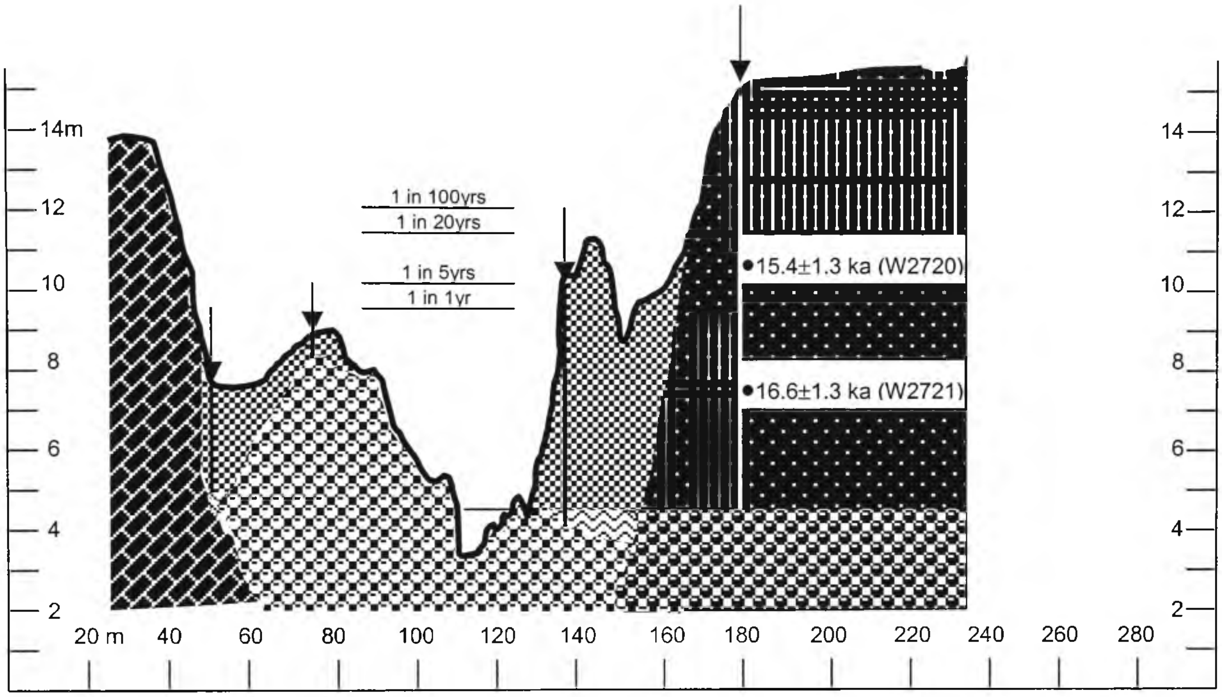


TAYLORS ARM SITE 9

Catchment Area 32,304ha

Surface Grain Size: 16±9mm
% Quartz: 85.63%
Subsurface D_{50}: 11.30 mm

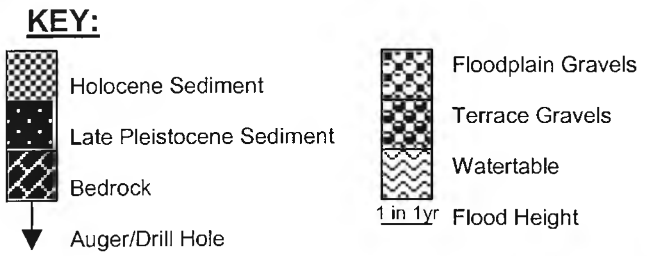


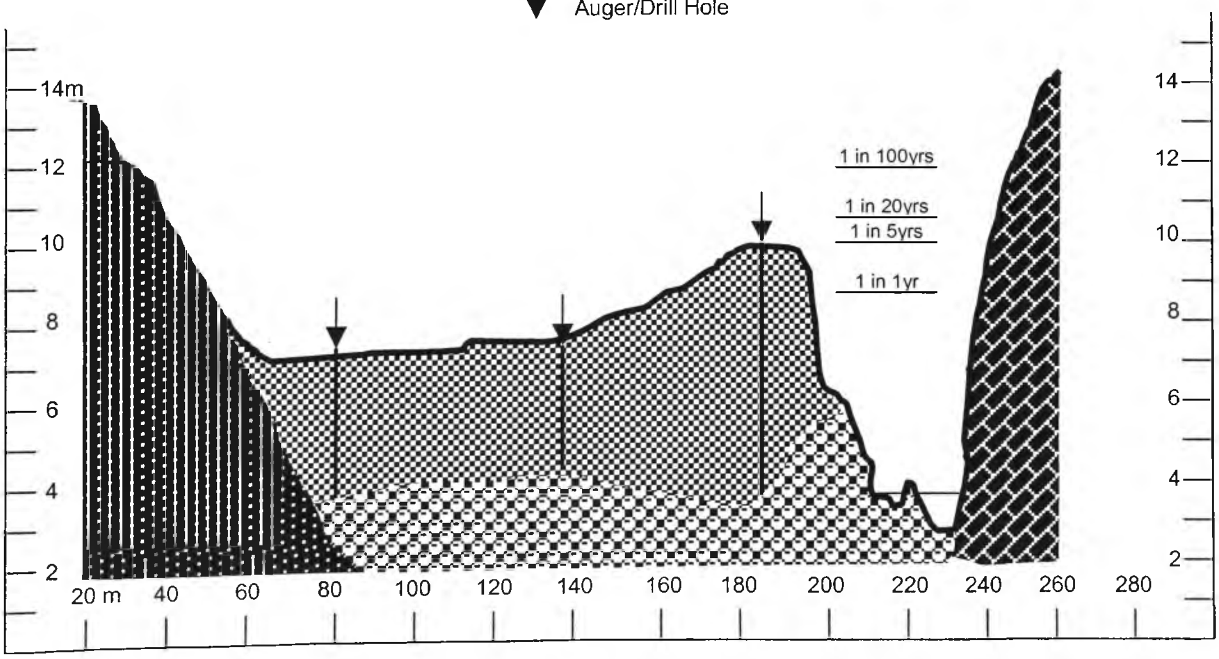


TAYLORS ARM SITE 10

Catchment Area 33,846ha

Surface Grain Size: 20±11mm
% Quartz: 85.48%
Subsurface D_{50}: 6.55 mm





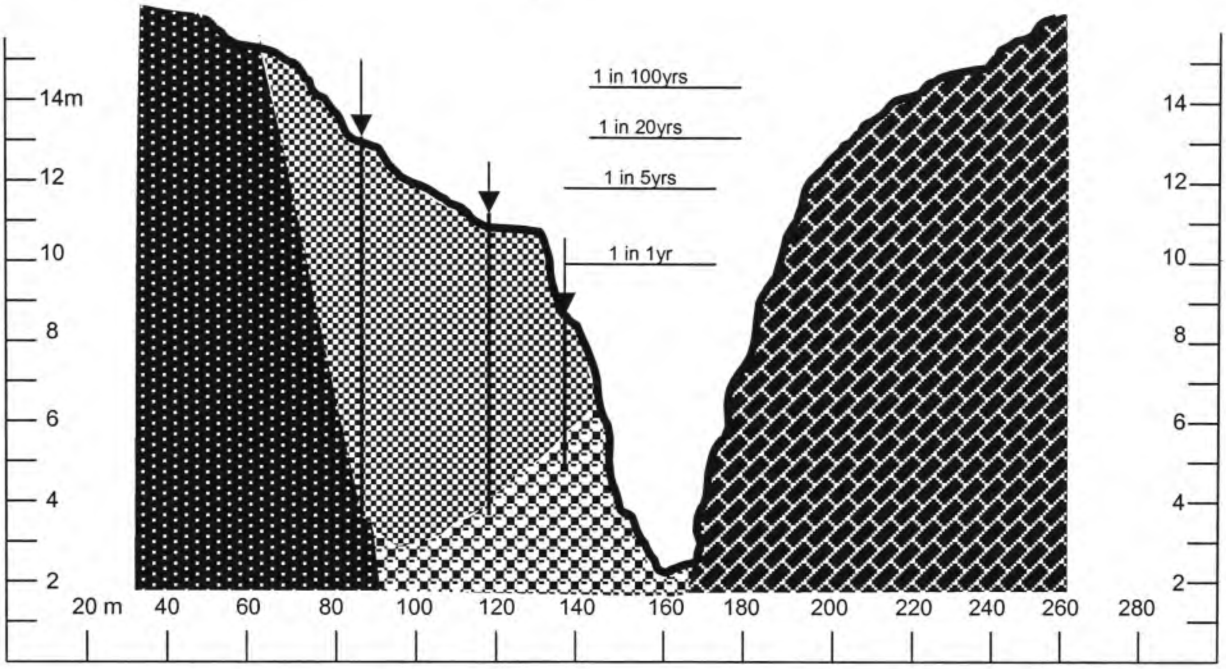
TAYLORS ARM SITE 11

Catchment Area 37,444ha

Surface Grain Size: 25±21mm
% Quartz: 87.80%
Subsurface D_{50}: 11.19mm

KEY:

- Holocene Sediment
- Late Pleistocene Sediment
- Bedrock
- Auger/Drill Hole
- Floodplain Gravels
- Terrace Gravels
- Watertable
- 1 in 1yr Flood Height

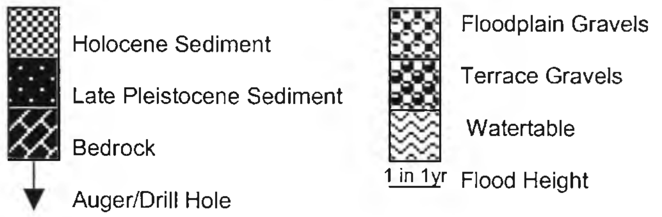


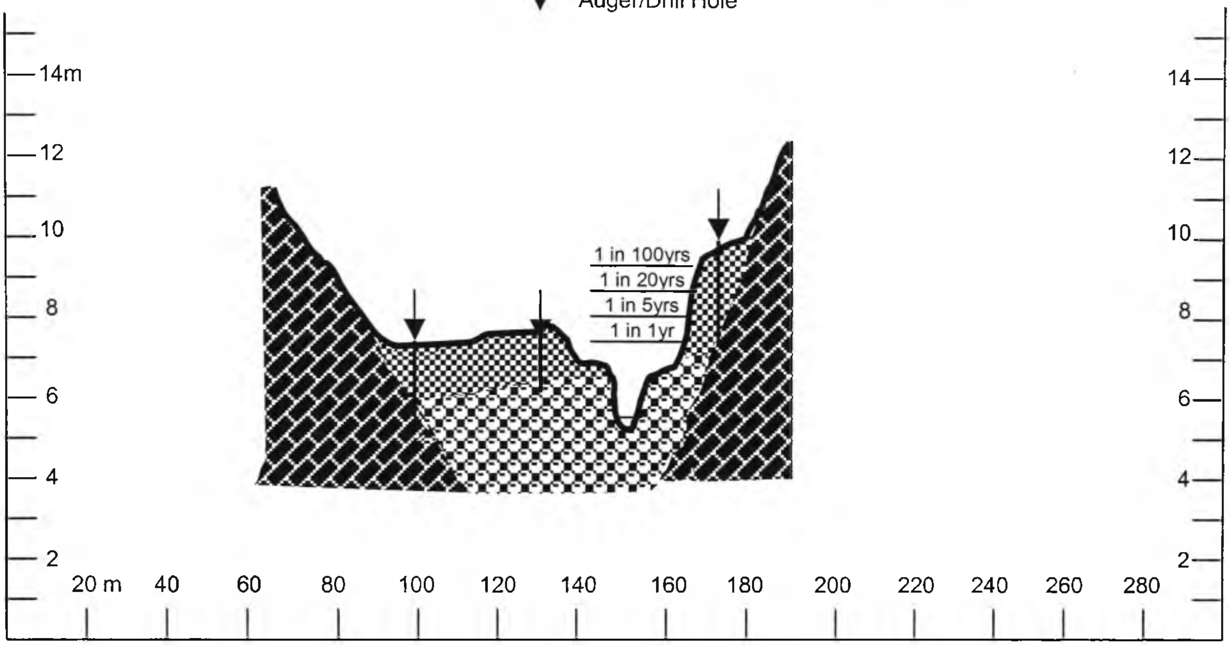
NORTH ARM SITE 1

Catchment Area 4,001ha

Surface Grain Size: 84±44mm
% Quartz: 12.50%
Subsurface D_{50}: 25.71mm

KEY:



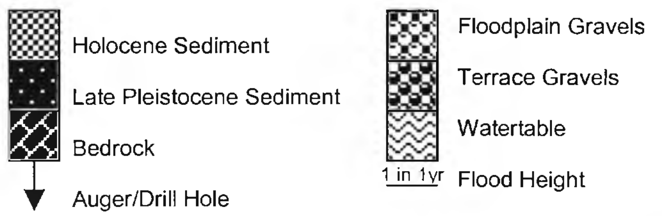


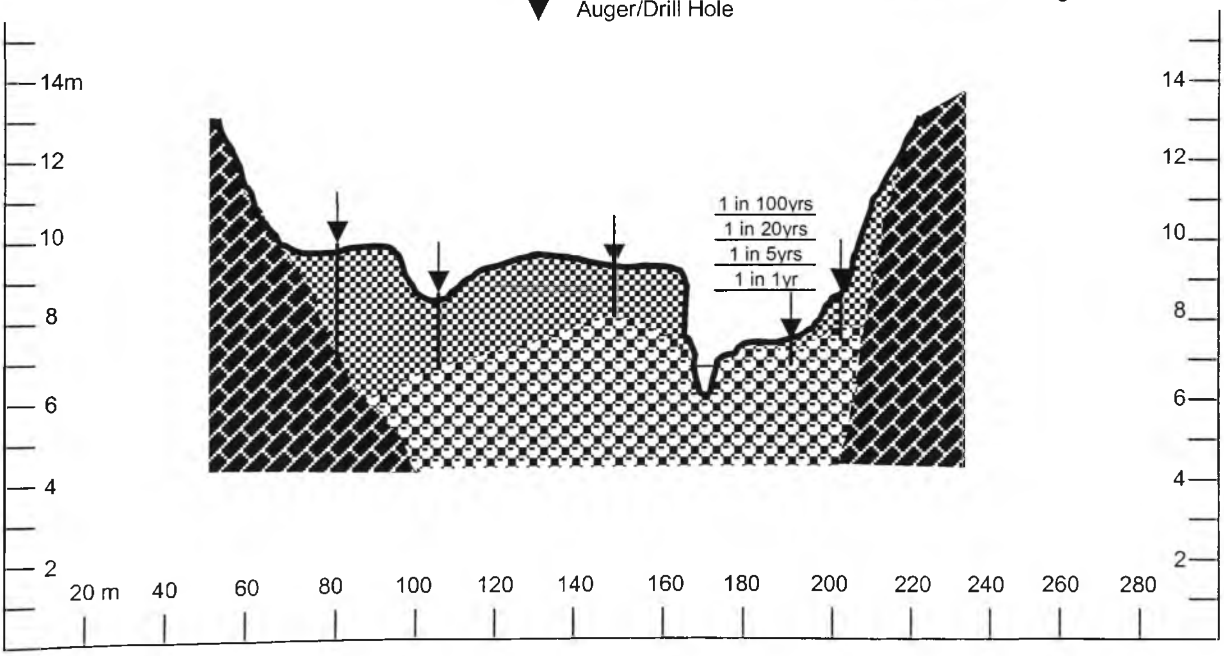
NORTH ARM SITE 2

Catchment Area 6,937ha

Surface Grain Size: 54±35 mm
% Quartz: 51.97%
Subsurface D_{50}: 17.22mm

KEY:





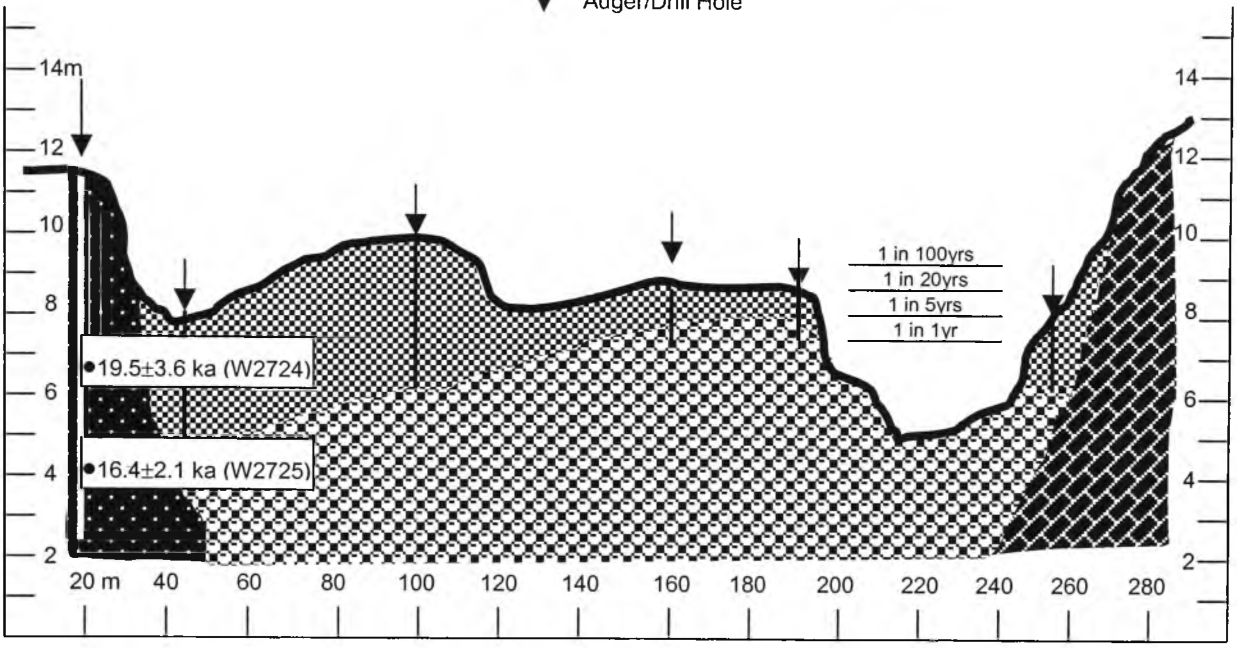
NORTH ARM SITE 3

Catchment Area 11,562ha

Surface Grain Size: 32±22mm
% Quartz: 76.47%
Subsurface D_{50}: 13.46mm

KEY:

- Holocene Sediment
- Late Pleistocene Sediment
- Bedrock
- Auger/Drill Hole
- Floodplain Gravels
- Terrace Gravels
- Watertable
- 1 in 1yr Flood Height



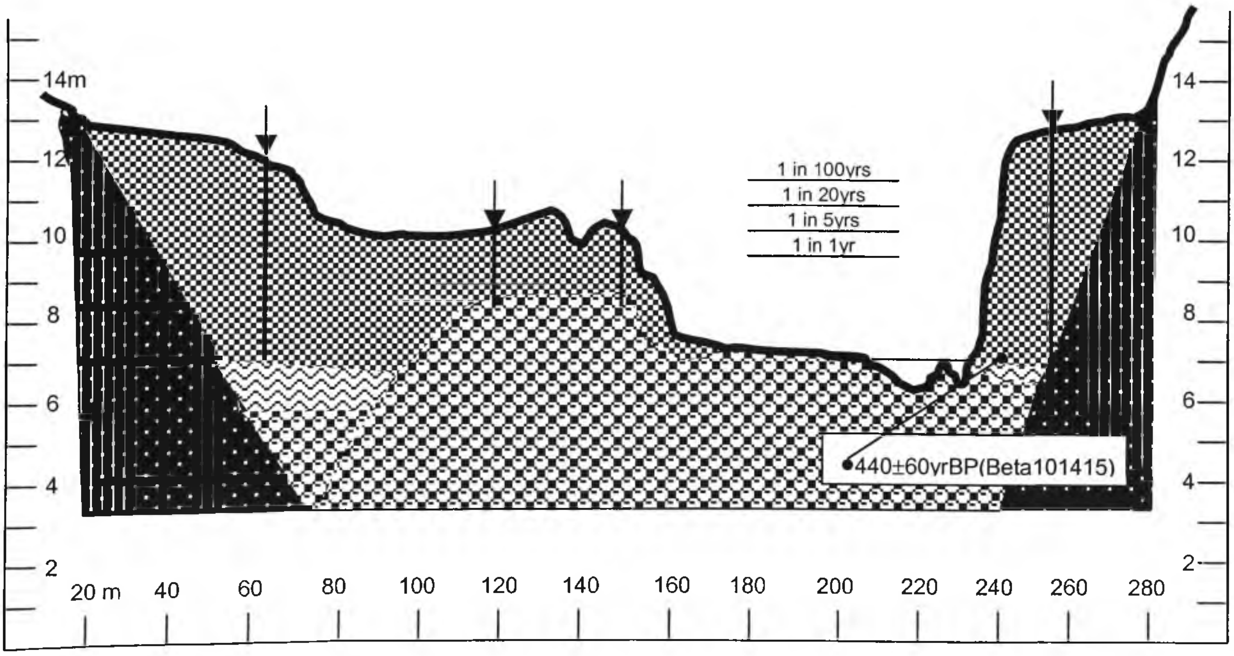
NORTH ARM SITE 4

Catchment Area 13,367ha

Surface Grain Size: 29±18mm
% Quartz: 91.80%
Subsurface D_{50}: 9.85 mm

KEY:

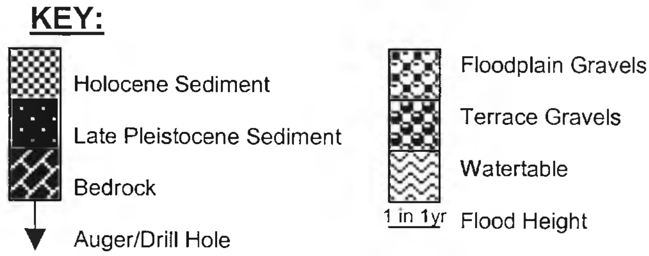
- Holocene Sediment
- Late Pleistocene Sediment
- Bedrock
- Auger/Drill Hole
- Floodplain Gravels
- Terrace Gravels
- Watertable
- 1 in 1yr Flood Height

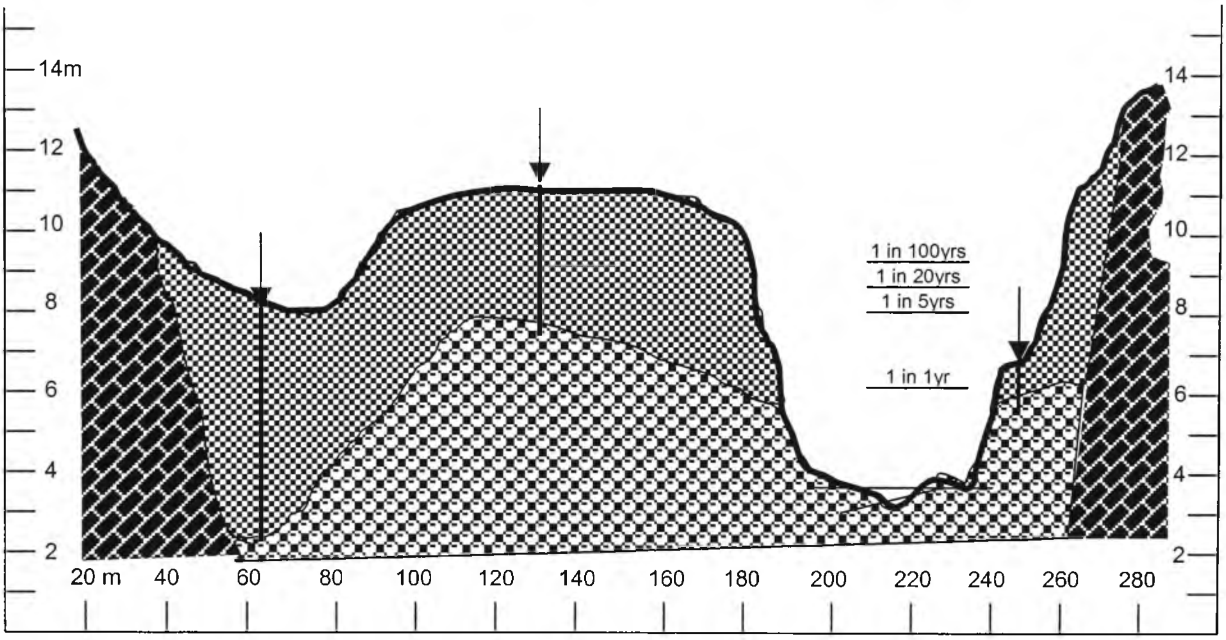


NORTH ARM SITE 5

Catchment Area 15,064

Surface Grain Size: 26±17mm
% Quartz: 93.44%
Subsurface D_{50}: 6.20MM

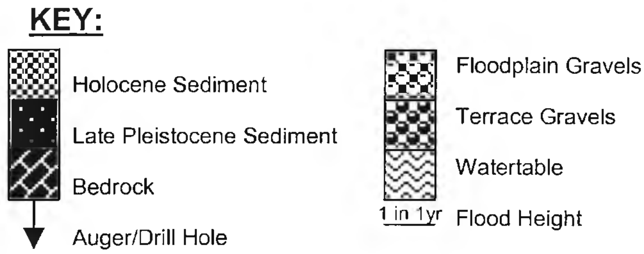


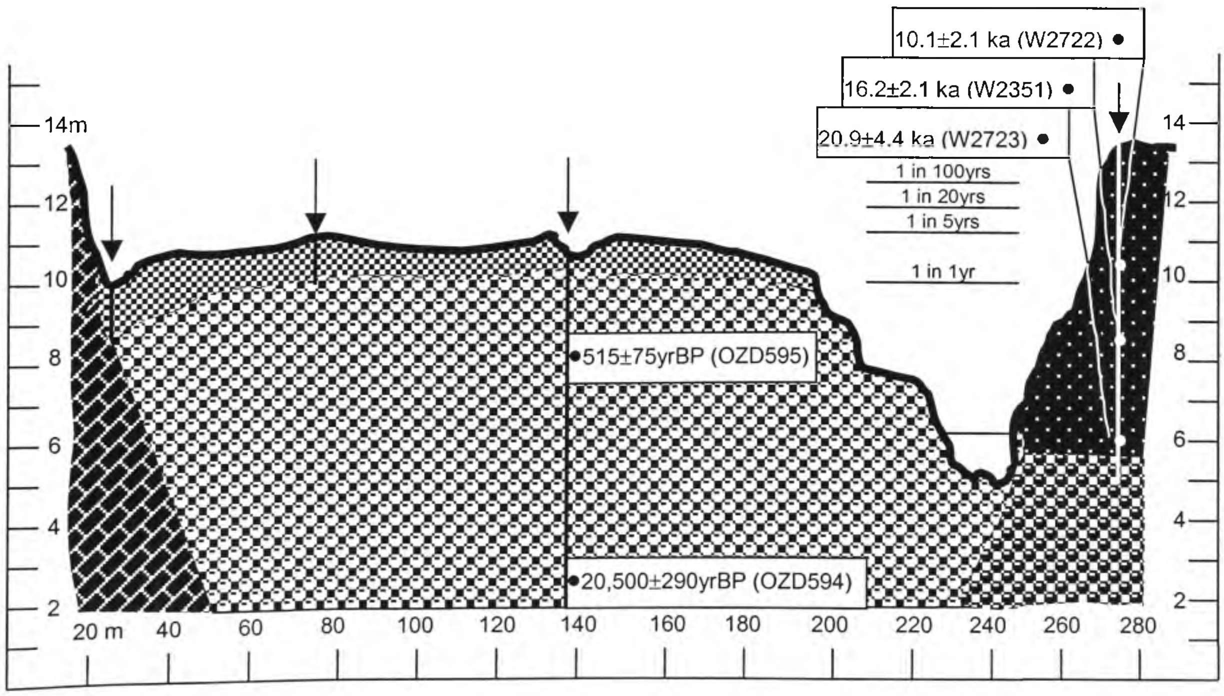


NORTH ARM SITE 6

Catchment Area 24,067ha

Surface Grain Size: 22±11mm
% Quartz: 95.08%
Subsurface D_{50}: 8.31mm

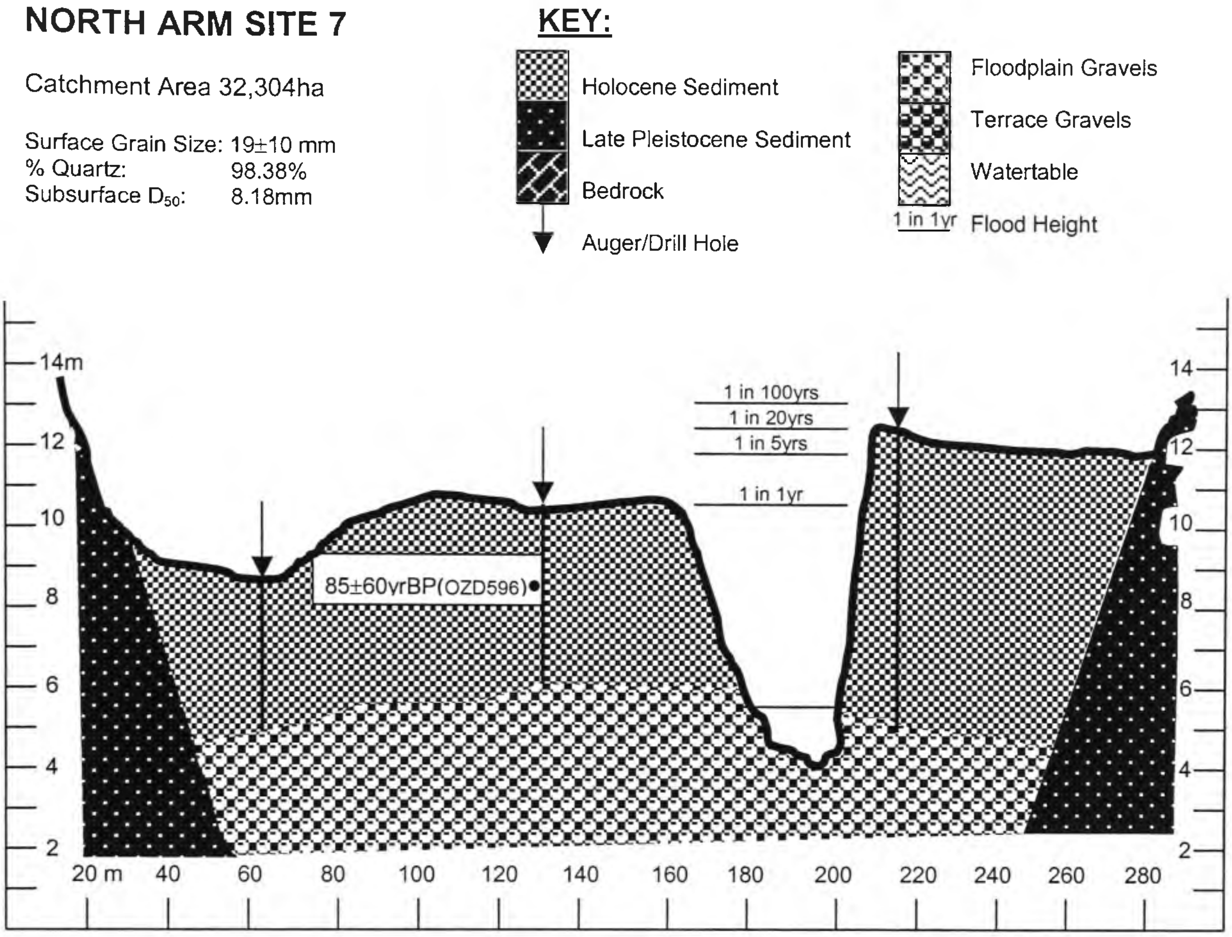




NORTH ARM SITE 7

Catchment Area 32,304ha

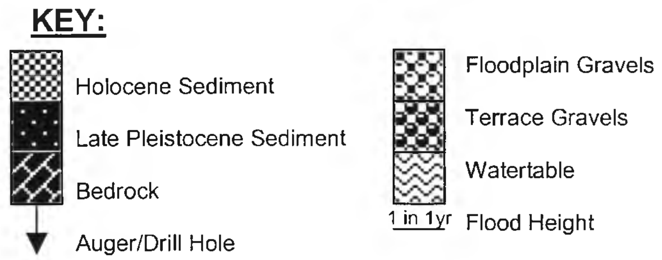
Surface Grain Size: 19±10 mm
% Quartz: 98.38%
Subsurface D_{50}: 8.18mm

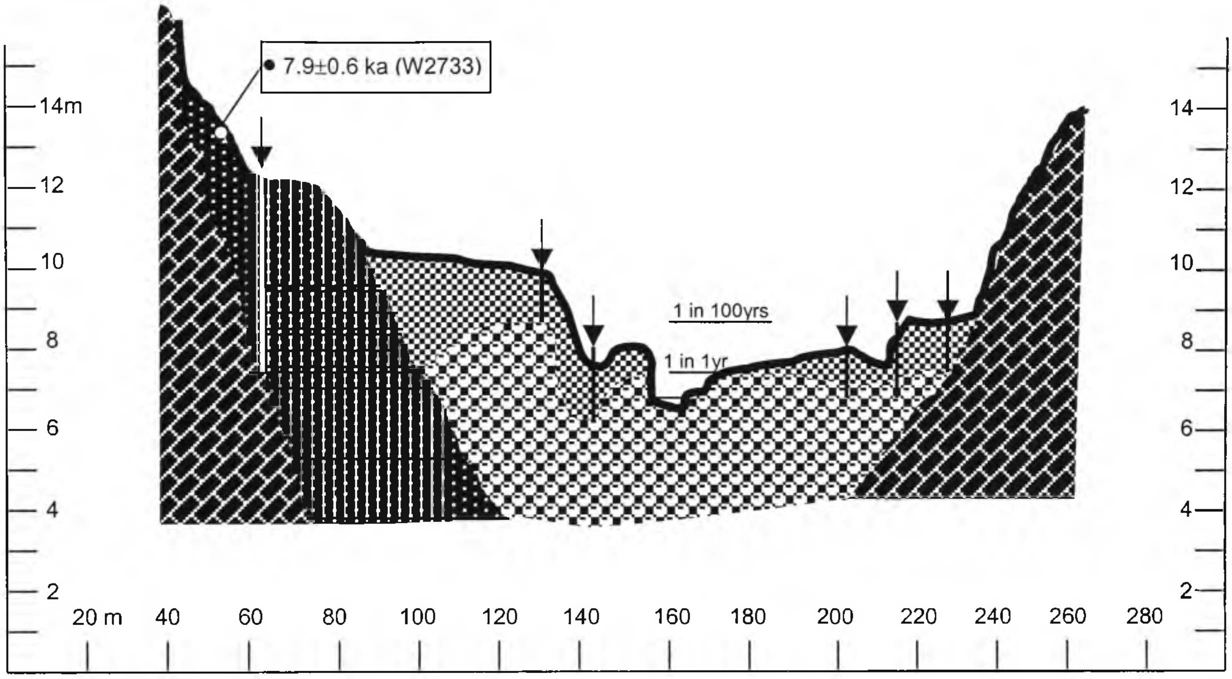


MISSABOTTI CREEK SITE 1

Catchment Area 214ha

Surface Grain Size: 81±32mm
% Quartz 50.00%
Subsurface D_{50}: 19.42mm

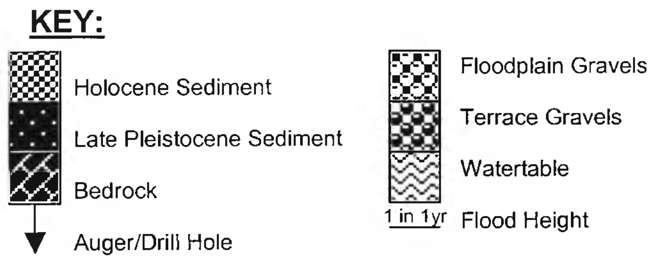


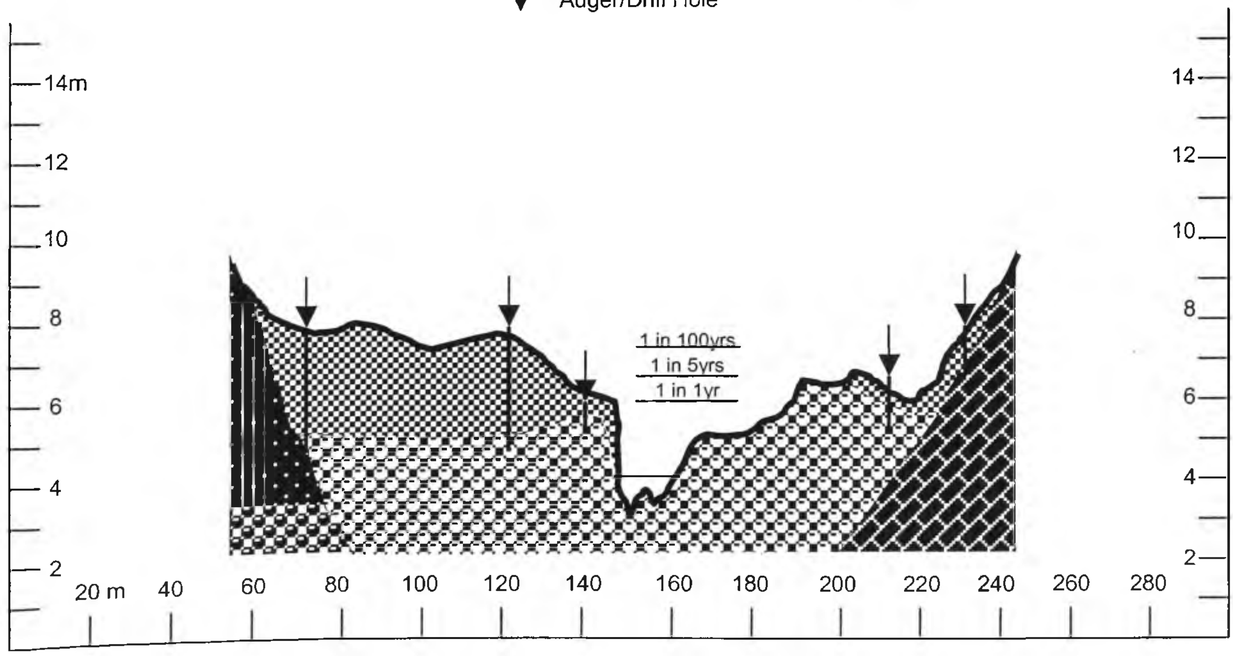


MISSABOTTI CREEK SITE 2

Catchment Area 4,024ha

Surface Grain Size: 36±21mm
% Quartz: 66.67%
Subsurface D_{50}: 10.86mm

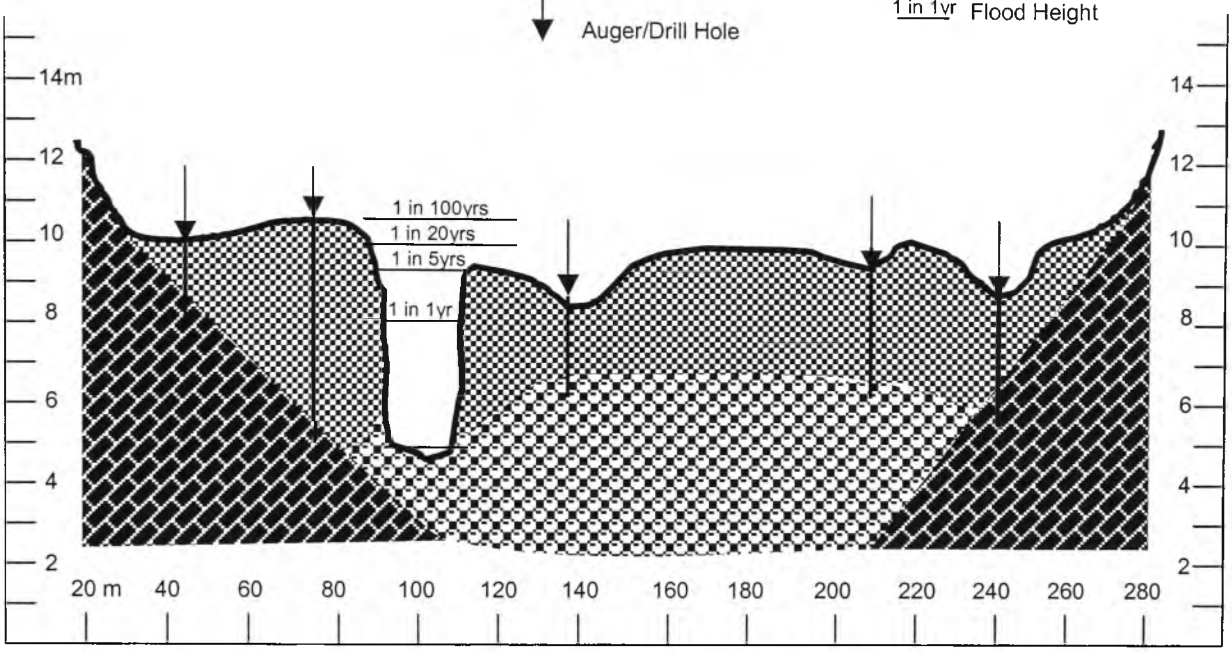




MISSABOTTI CREEK SITE 3

Catchment Area 6,182ha

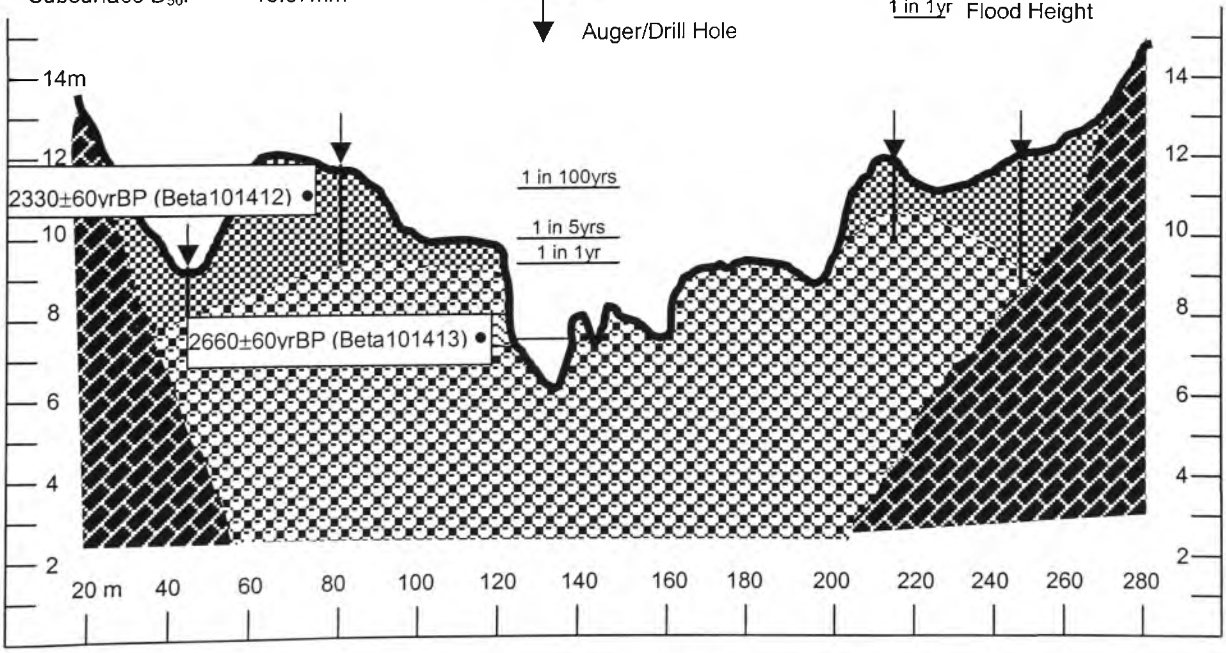
Surface Grain Size: 37±26mm
% Quartz: 73.33%
Subsurface D_{50}: 10.86mm



MISSABOTTI CREEK SITE 4

Catchment Area 7,048ha

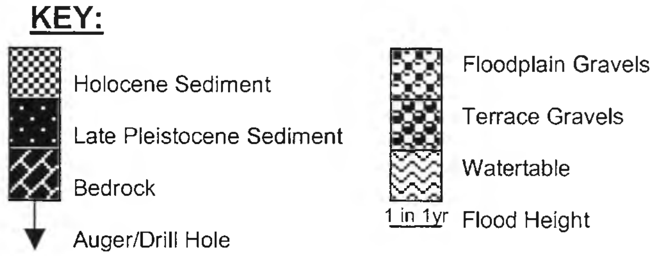
Surface Grain Size: 22±14mm
% Quartz 91.67.05%
Subsurface D_{50}: 18.37mm

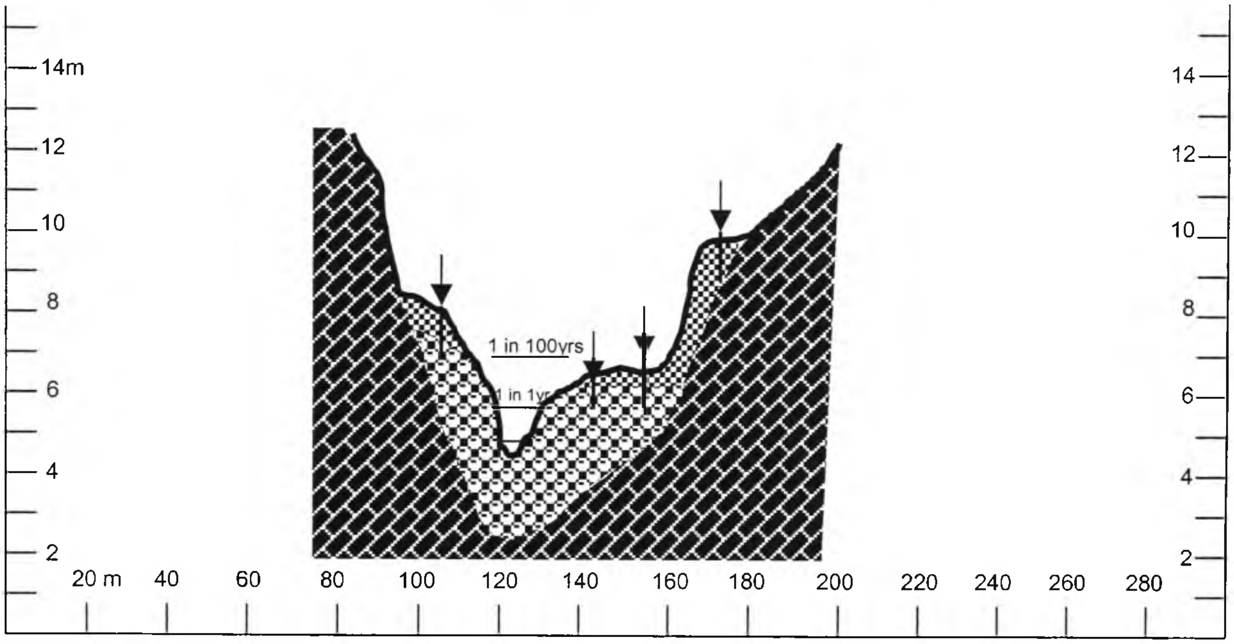


SOUTH ARM SITE 1

Catchment Area 847ha

Surface Grain Size: 117±90 mm
% Quartz: 1.67%
Subsurface D_{50}: 26.37mm

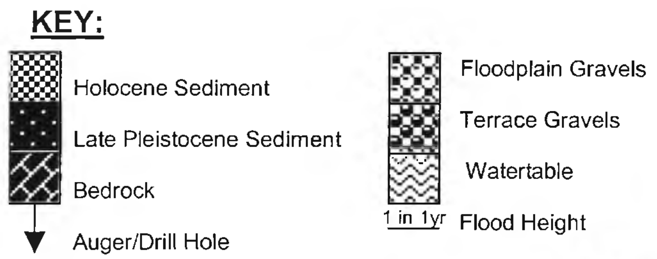


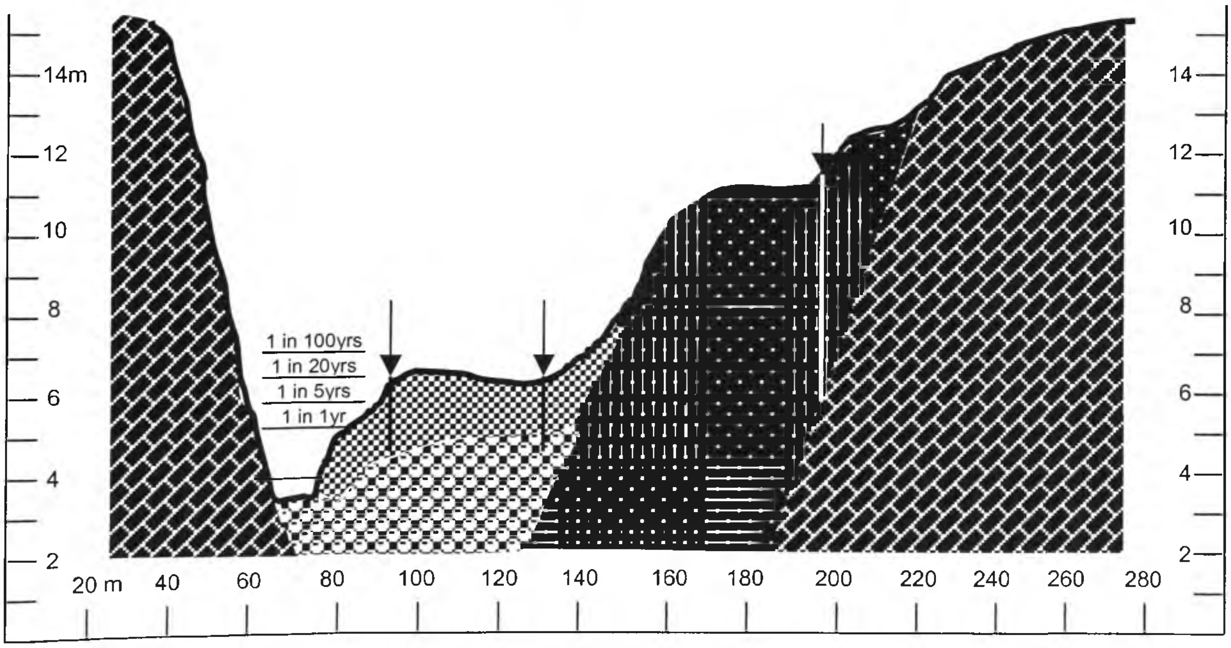


SOUTH ARM SITE 2

Catchment Area 2,435ha

Surface Grain Size: 77±32mm
% Quartz: 4.10%
Subsurface D_{50}: 41.06mm

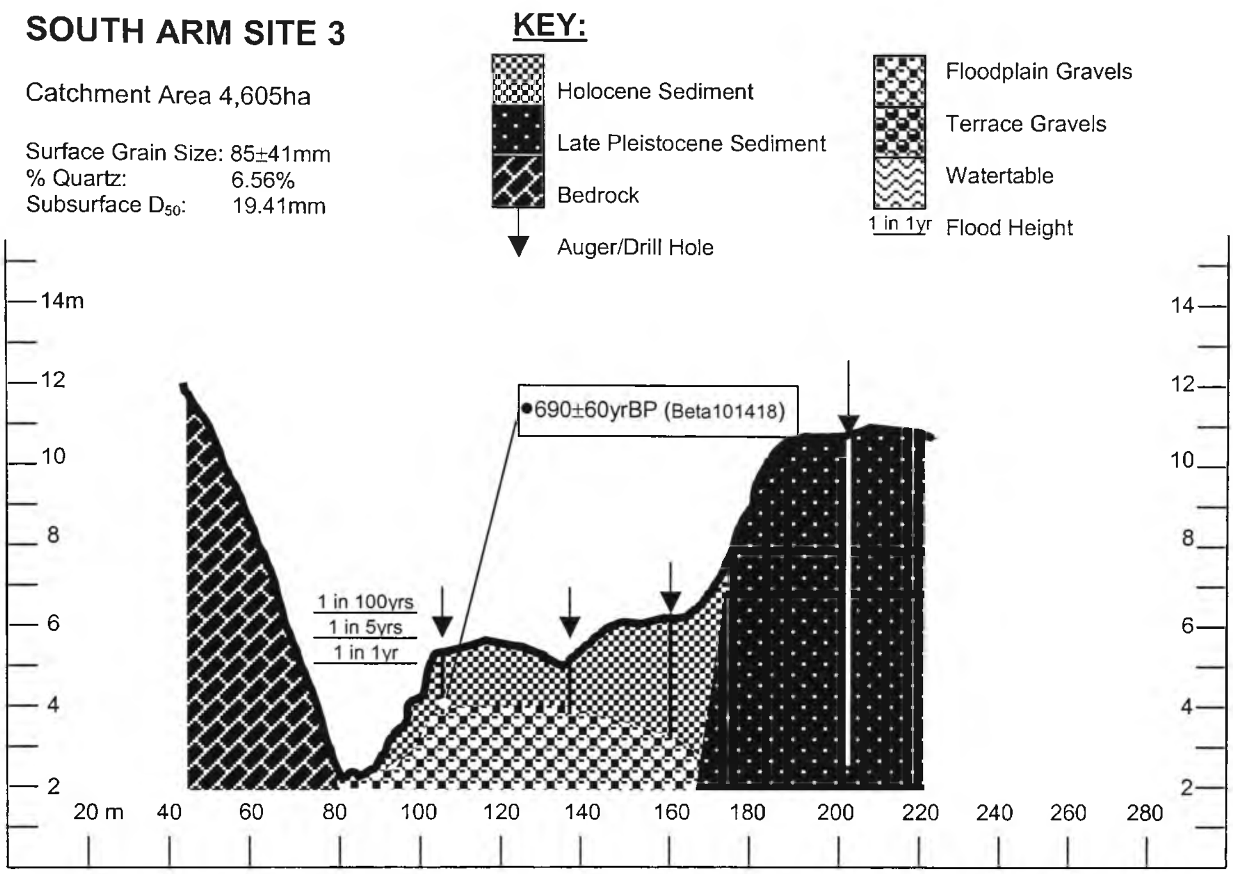




SOUTH ARM SITE 3

Catchment Area 4,605ha

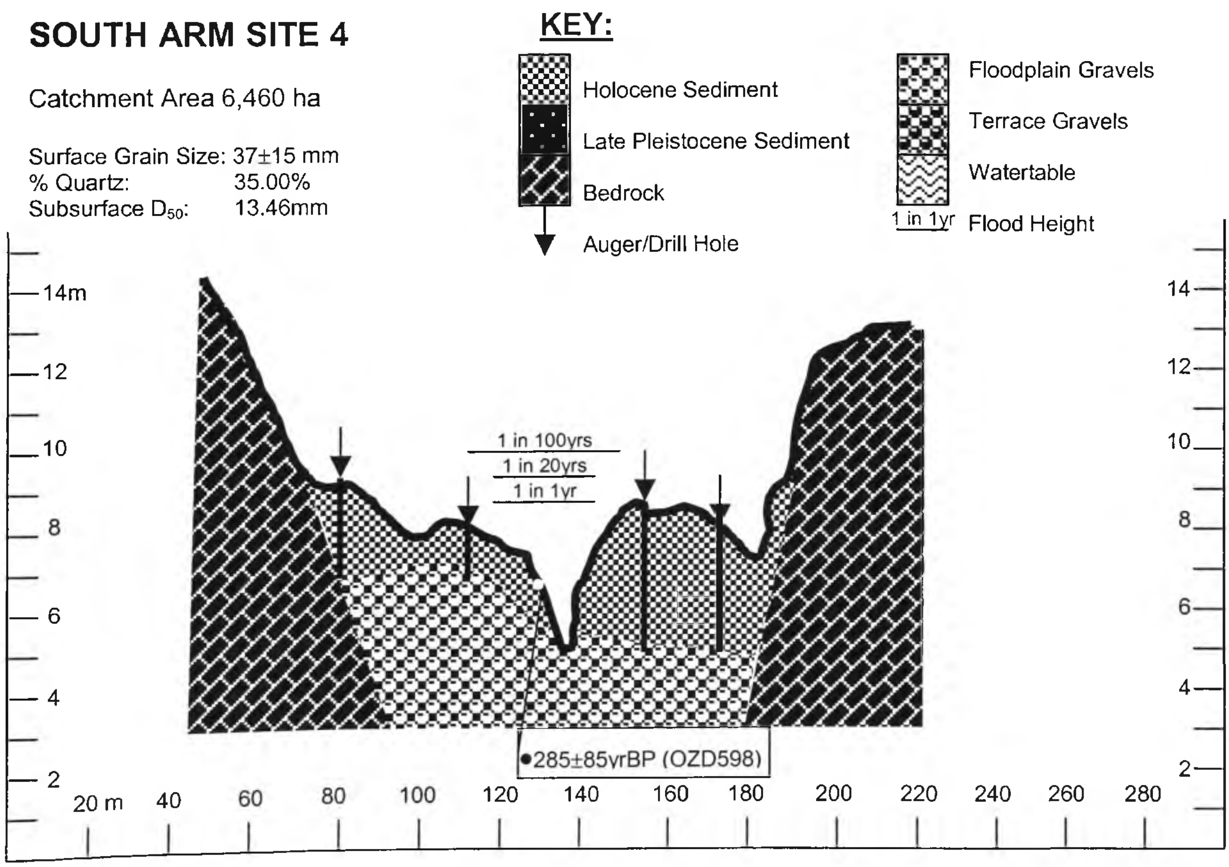
Surface Grain Size: 85±41mm
% Quartz: 6.56%
Subsurface D_{50}: 19.41mm

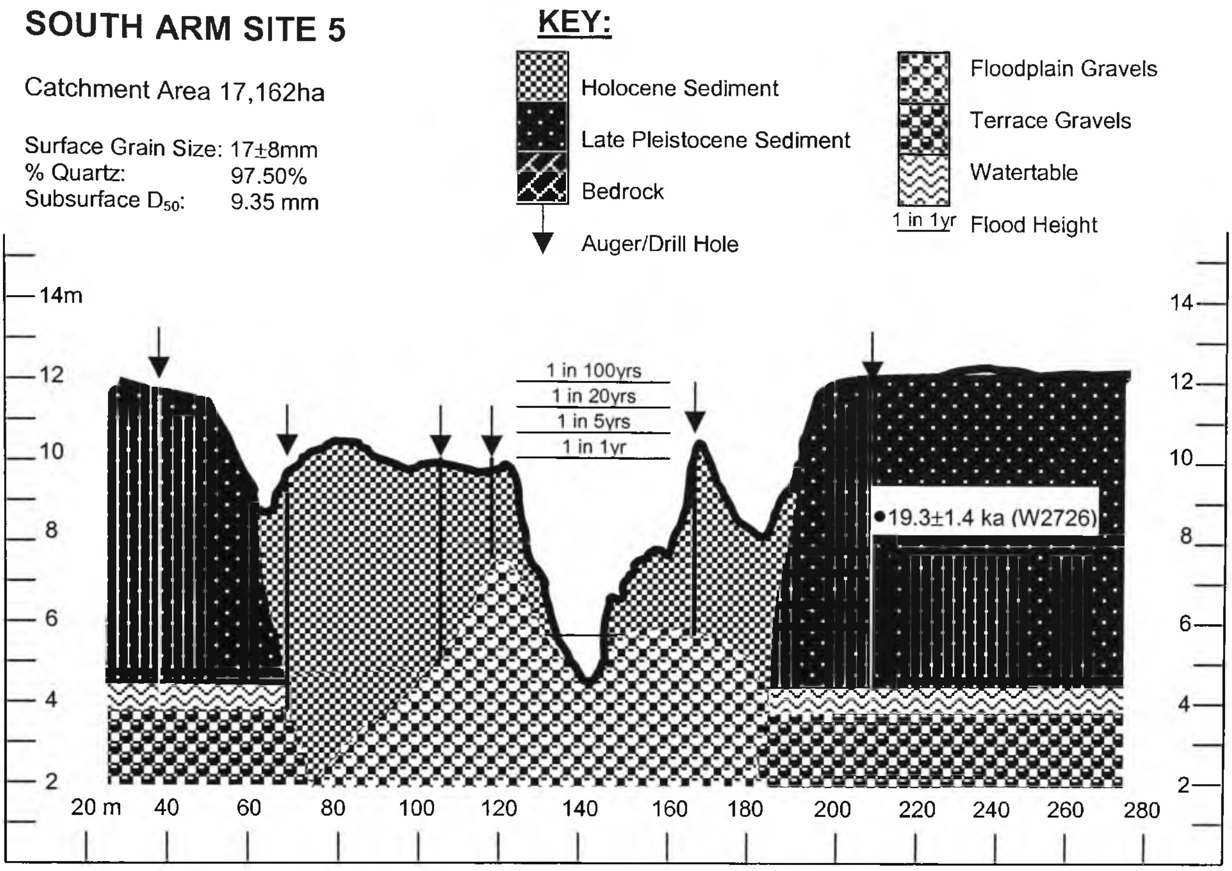


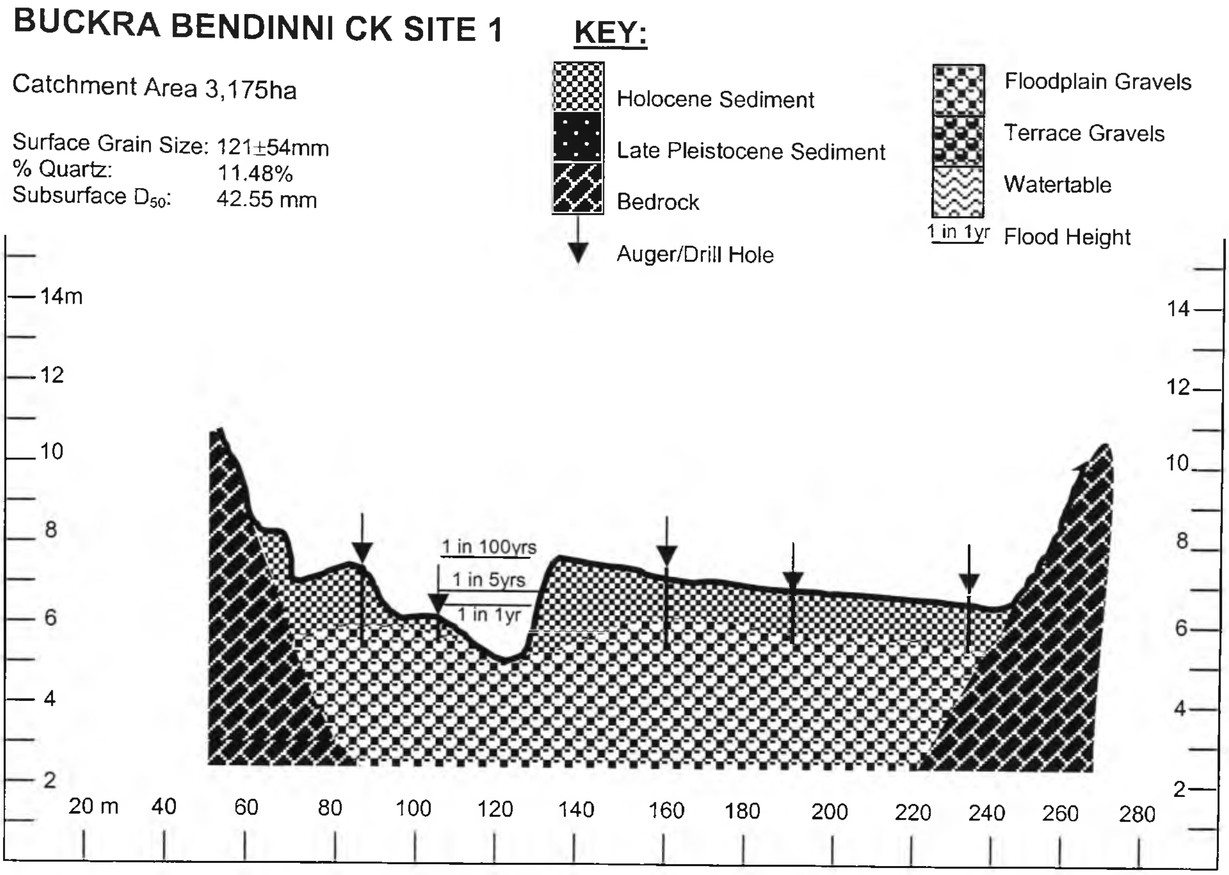
SOUTH ARM SITE 4

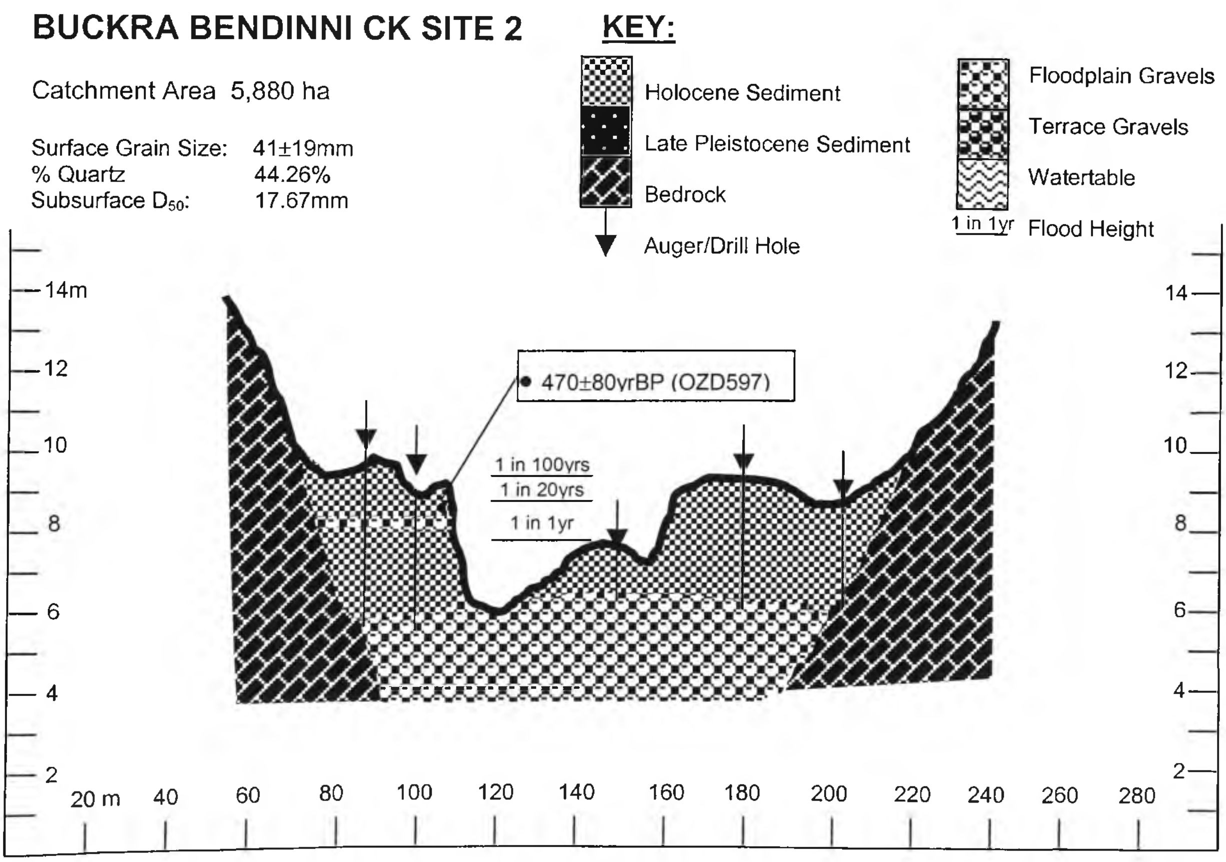
Catchment Area 6,460 ha

Surface Grain Size: 37±15 mm
% Quartz: 35.00%
Subsurface D_{50}: 13.46mm




SOUTH ARM SITE 5
Catchment Area 17,162ha
Surface Grain Size: 17±8mm
% Quartz: 97.50%
Subsurface D50: 9.35 mm
KEY:
Holocene Sediment
Late Pleistocene Sediment
Bedrock
Auger/Drill Hole
Floodplain Gravels
Terrace Gravels
Watertable
1 in 1yr Flood Height
1 in 100yrs
1 in 20yrs
1 in 5yrs
1 in 1yr
19.3±1.4 ka (W2726)
14m
12
10
8
6
4
2
20 m
40
60
80
100
120
140
160
180
200
220
240
260
280

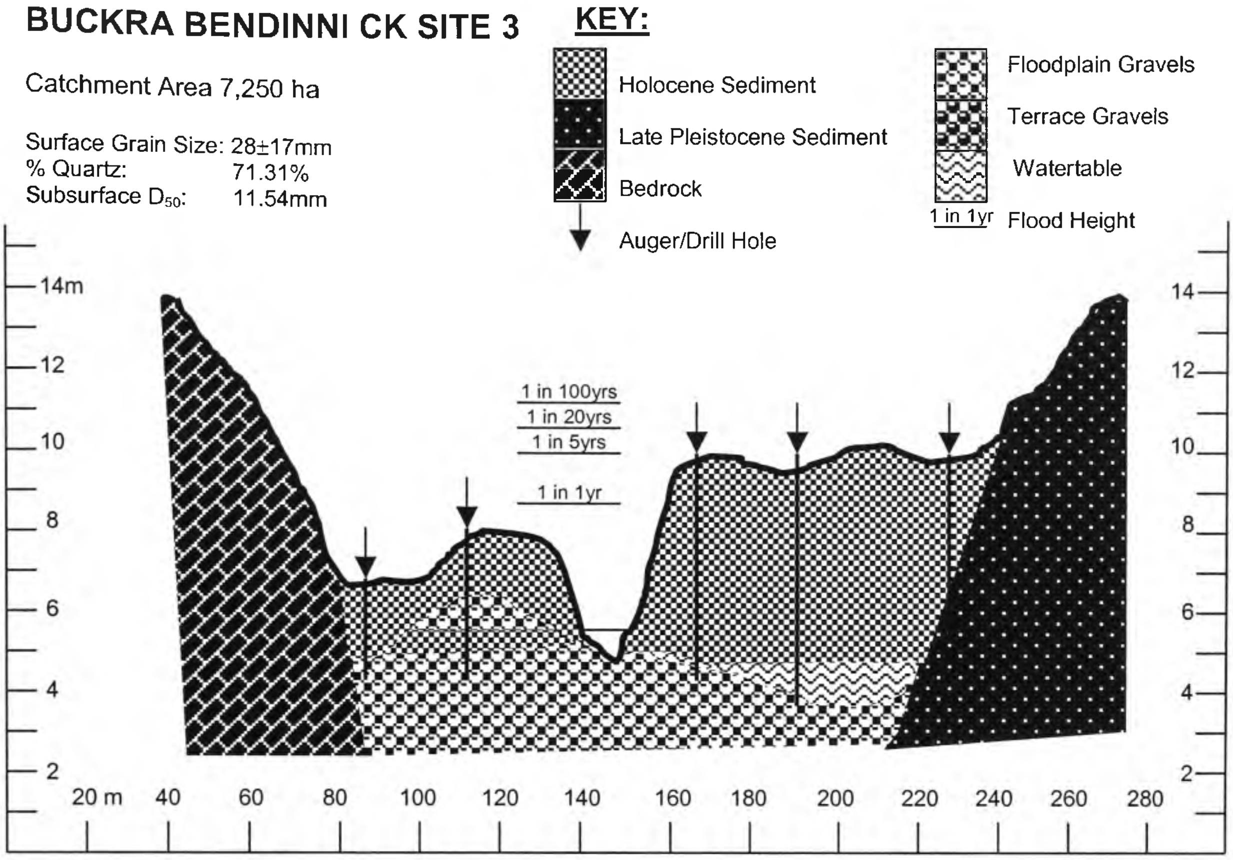

BUCKRA BENDINNI CK SITE 1
Catchment Area 3,175ha
Surface Grain Size: 121±54mm
% Quartz: 11.48%
Subsurface D50: 42.55 mm
KEY:
Holocene Sediment
Late Pleistocene Sediment
Bedrock
Auger/Drill Hole
Floodplain Gravels
Terrace Gravels
Watertable
1 in 1yr Flood Height
1 in 100yrs
1 in 5yrs
1 in 1yr
14m
12
10
8
6
4
2
20 m
40
60
80
100
120
140
160
180
200
220
240
260
280


BUCKRA BENDINNI CK SITE 2
Catchment Area 5,880 ha
Surface Grain Size: 41±19mm
% Quartz 44.26%
Subsurface D50: 17.67mm
KEY:
Holocene Sediment
Late Pleistocene Sediment
Bedrock
Auger/Drill Hole
Floodplain Gravels
Terrace Gravels
Watertable
1 in 1yr Flood Height
470±80yrBP (OZD597)
1 in 100yrs
1 in 20yrs
1 in 1yr
14m
12
10
8
6
4
2
20 m
40
60
80
100
120
140
160
180
200
220
240
260
280

BUCKRA BENDINNI CK SITE 3

Catchment Area 7,250 ha

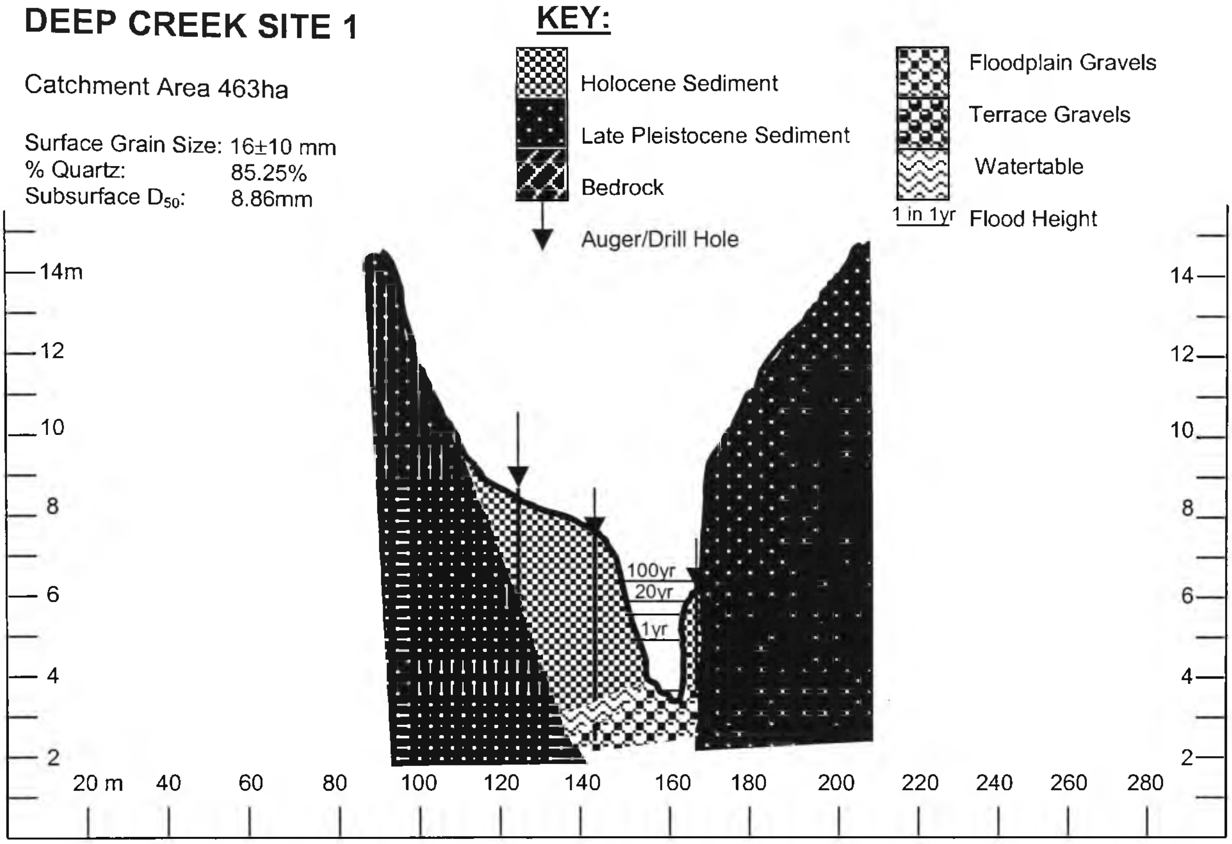
Surface Grain Size: 28±17mm
% Quartz: 71.31%
Subsurface D_{50}: 11.54mm



DEEP CREEK SITE 1

Catchment Area 463ha

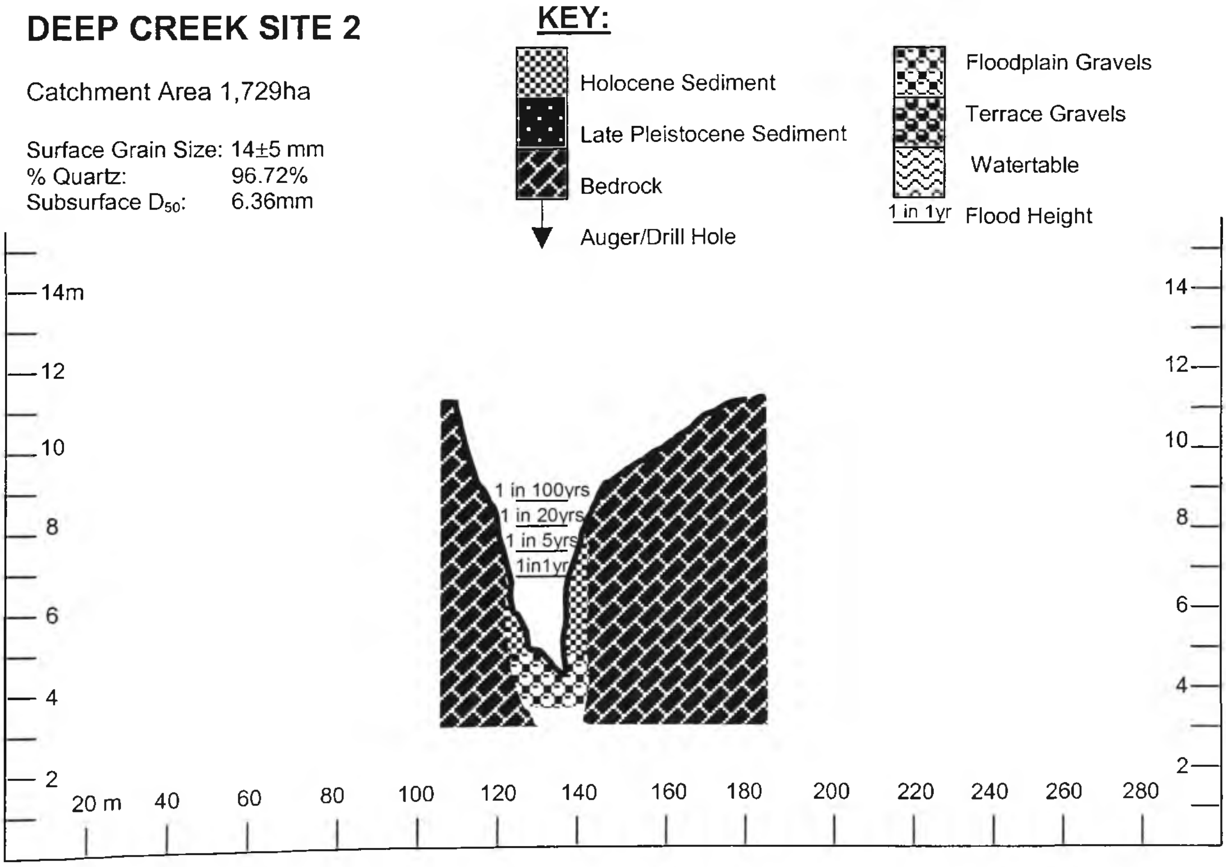
Surface Grain Size: 16±10 mm
% Quartz: 85.25%
Subsurface D_{50}: 8.86mm

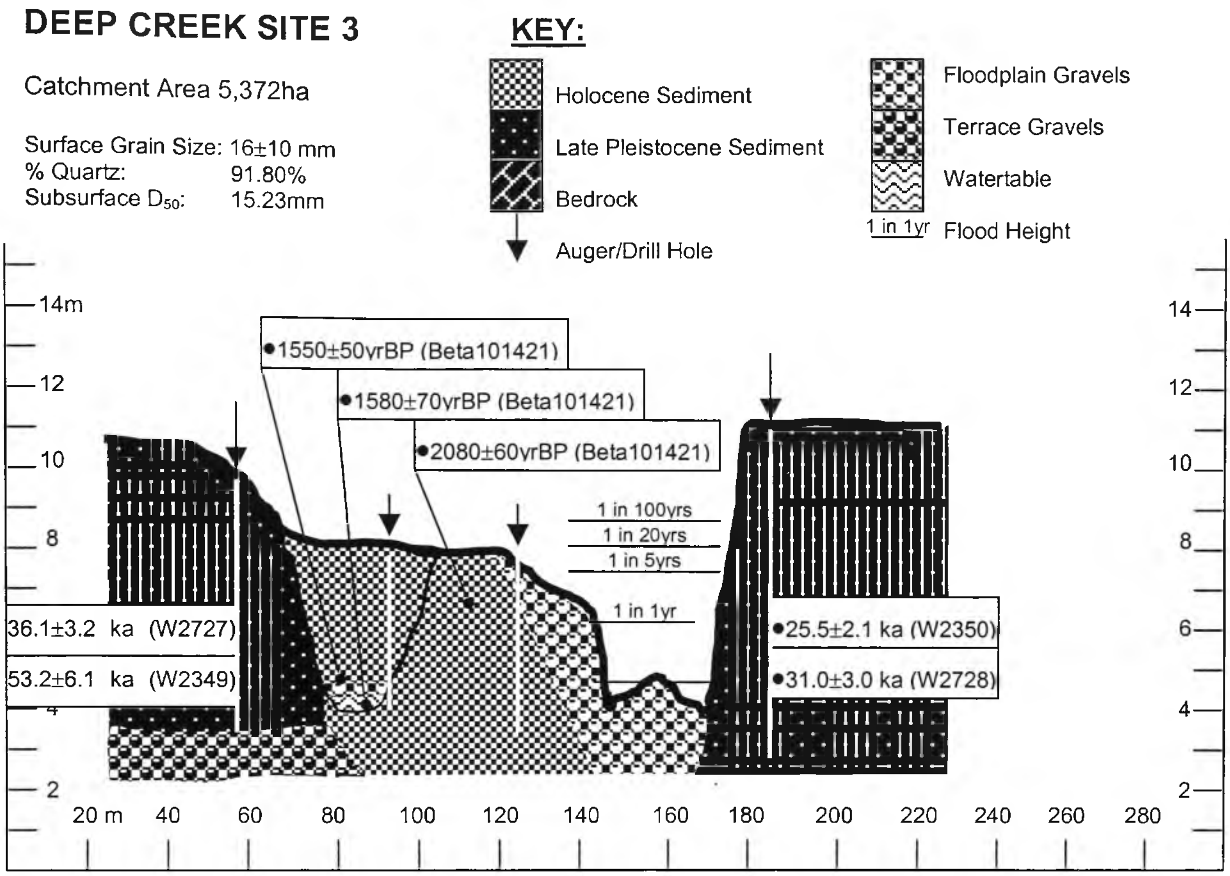


DEEP CREEK SITE 2

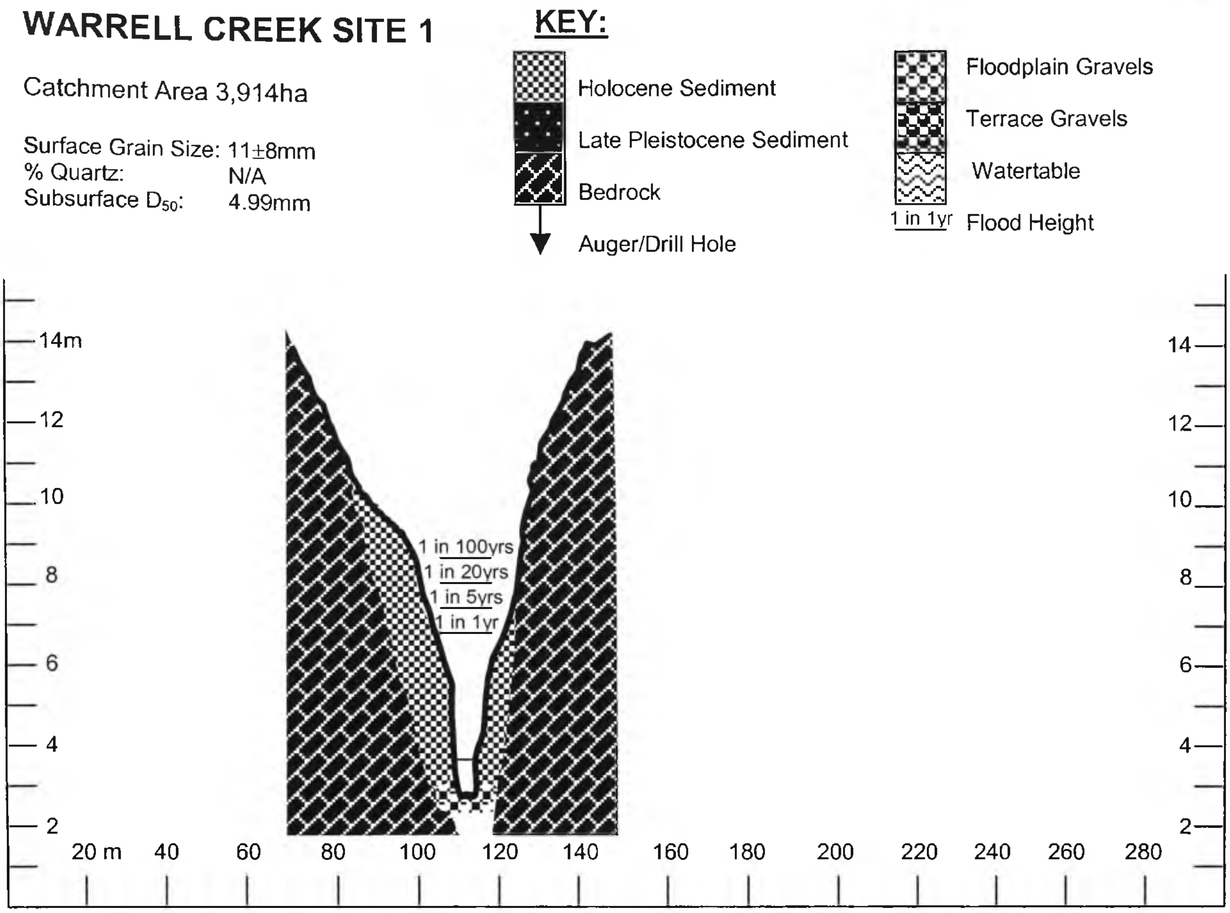
Catchment Area 1,729ha

Surface Grain Size: 14±5 mm
% Quartz: 96.72%
Subsurface D_{50}: 6.36mm

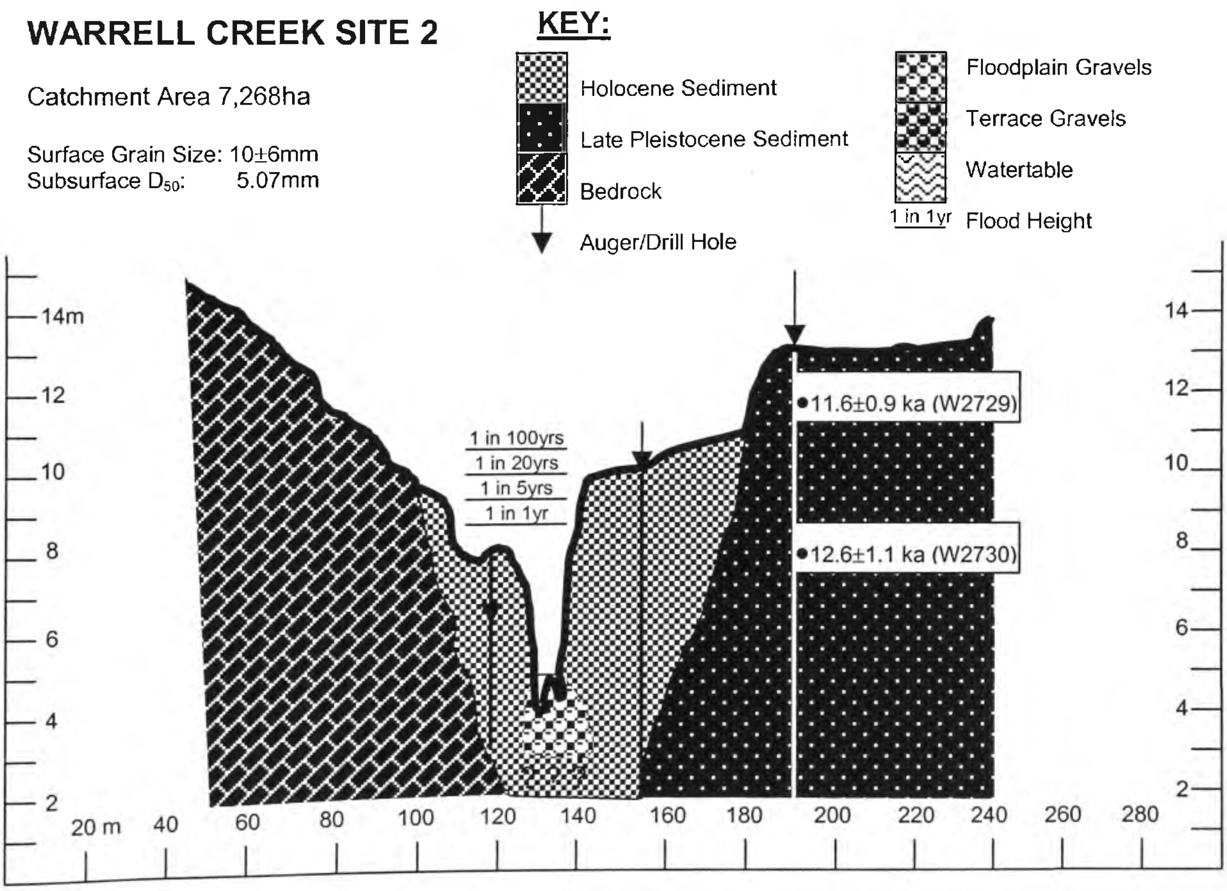


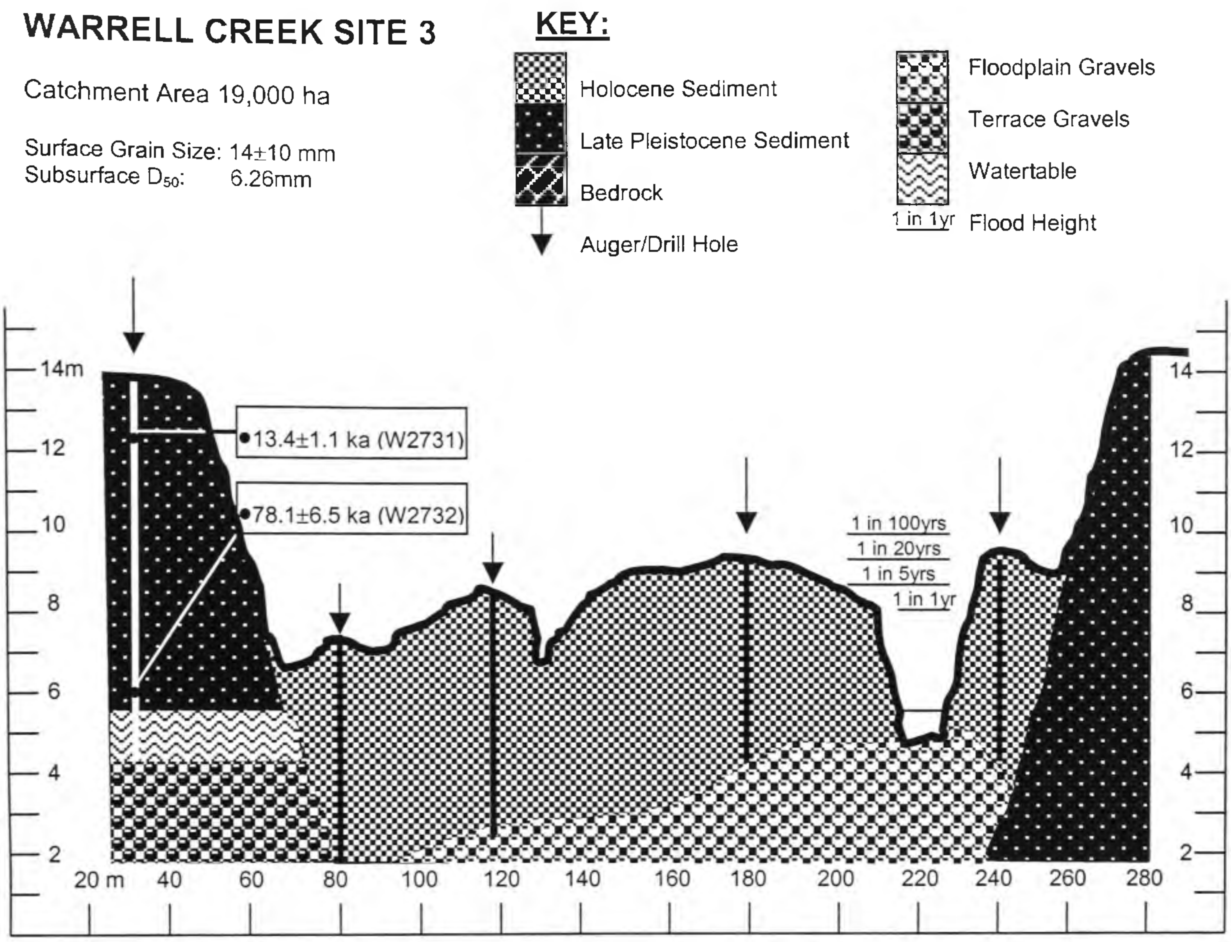

DEEP CREEK SITE 3
Catchment Area 5,372ha
Surface Grain Size: 16±10 mm
% Quartz: 91.80%
Subsurface D50: 15.23mm
KEY:
Holocene Sediment
Late Pleistocene Sediment
Bedrock
Auger/Drill Hole
Floodplain Gravels
Terrace Gravels
Watertable
1 in 1yr Flood Height
•1550±50yrBP (Beta101421)
•1580±70yrBP (Beta101421)
•2080±60yrBP (Beta101421)
1 in 100yrs
1 in 20yrs
1 in 5yrs
1 in 1yr
36.1±3.2 ka (W2727)
53.2±6.1 ka (W2349)
•25.5±2.1 ka (W2350)
•31.0±3.0 ka (W2728)
14m
12
10
8
2
20 m
40
60
80
100
120
140
160
180
200
220
240
260
280

WARRELL CREEK SITE 1



WARRELL CREEK SITE 2



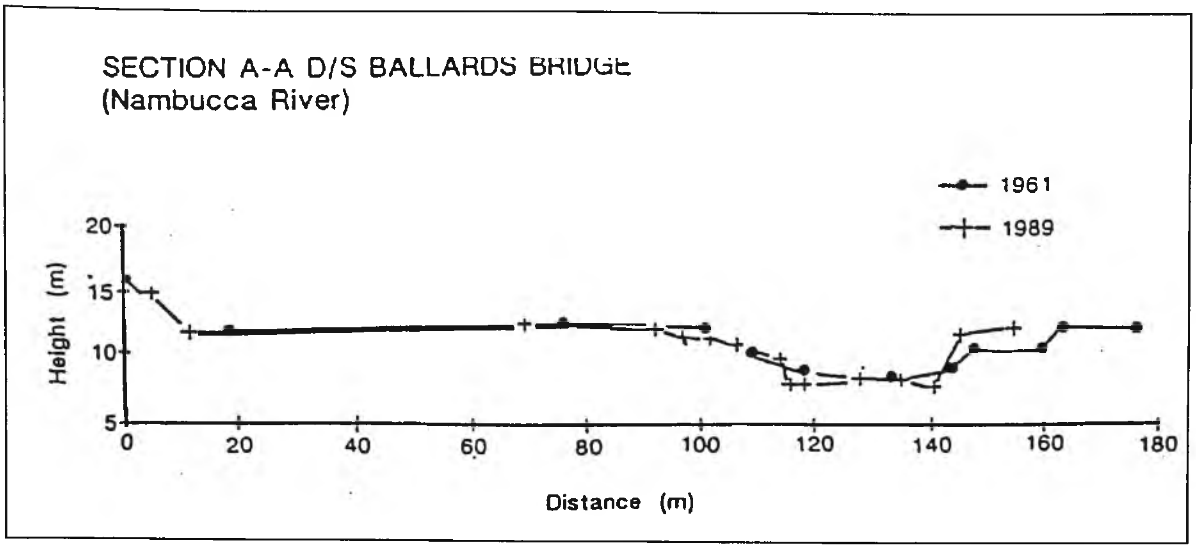


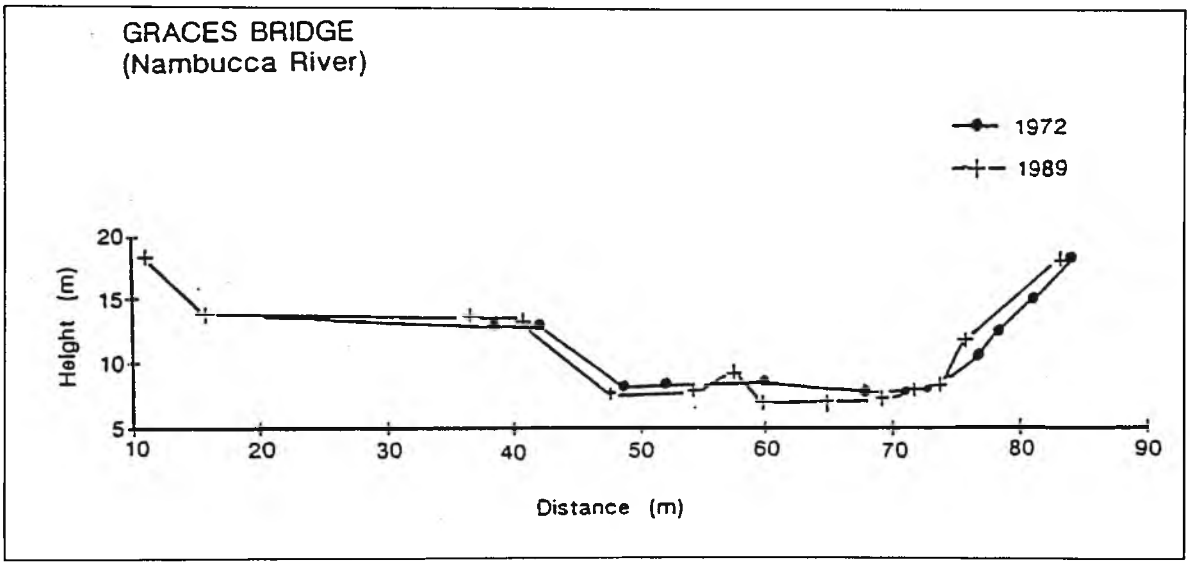
WARRELL CREEK SITE 3
Catchment Area 19,000 ha
Surface Grain Size: 14±10 mm
Subsurface D50: 6.26mm
KEY:
Holocene Sediment
Late Pleistocene Sediment
Bedrock
Auger/Drill Hole
Floodplain Gravels
Terrace Gravels
Watertable
1 in 1yr Flood Height
13.4±1.1 ka (W2731)
78.1±6.5 ka (W2732)
1 in 100yrs
1 in 20yrs
1 in 5yrs
1 in 1yr
14m
12
10
8
6
4
2
20 m
40
60
80
100
120
140
160
180
200
220
240
260
280

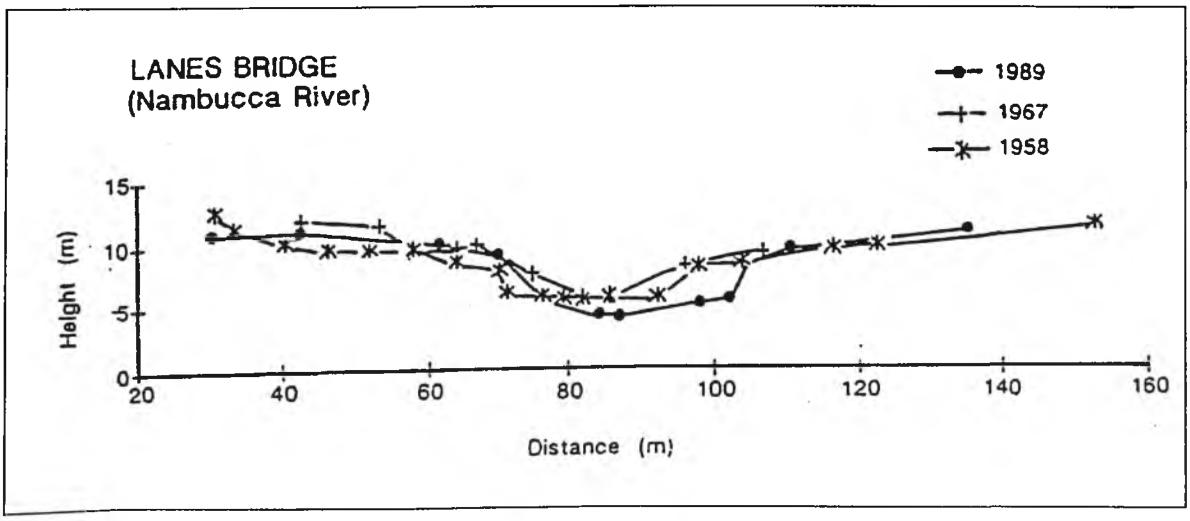
APPENDIX 9

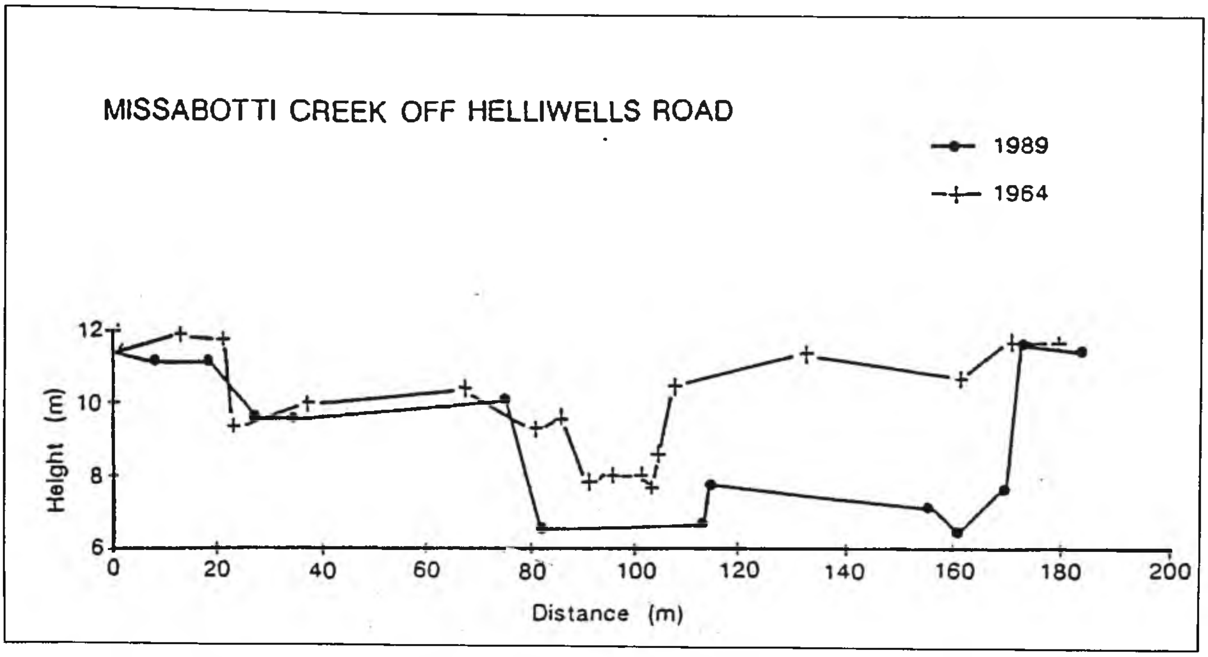
STREAM CROSS SECTIONS INDICATING CHANNEL BED LOWERING

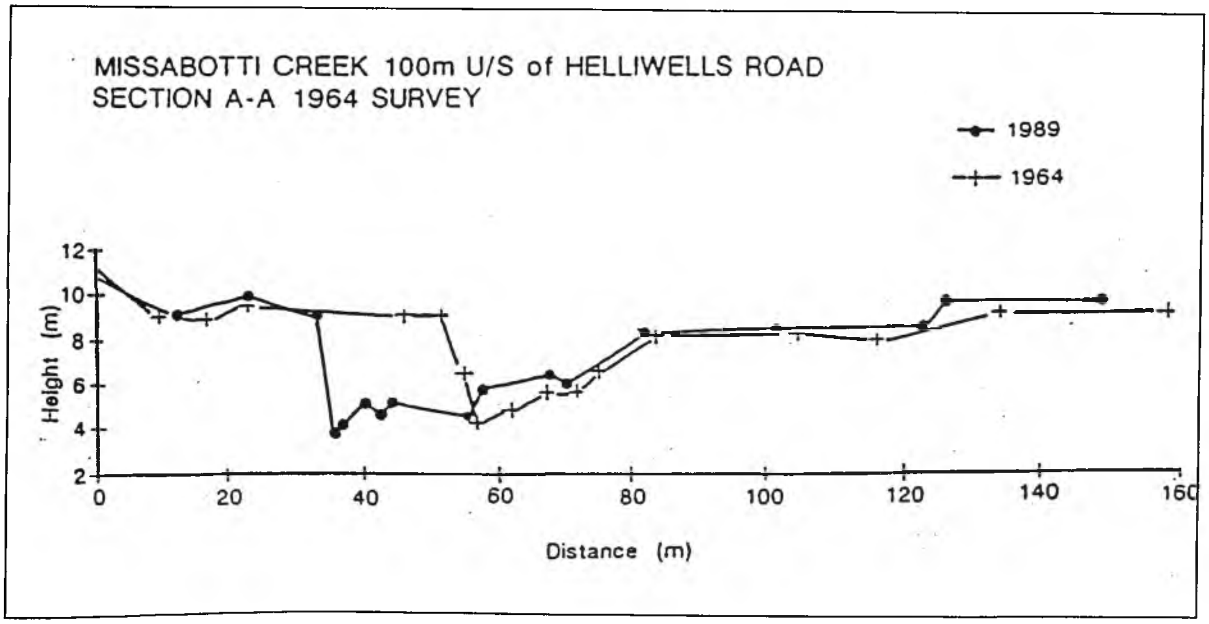
(Source: Resource Planning, 1989)


SECTION A-A D/S BALLARDS BRIDGE
(Nambucca River)
1961
1989
Height (m)
Distance (m)


GRACES BRIDGE
(Nambucca River)
1972
1989
Height (m)
Distance (m)


LANES BRIDGE
(Nambucca River)
1989
1967
1958
Height (m)
Distance (m)


MISSABOTTI CREEK OFF HELLIWELLS ROAD
1989
1964
Height (m)
12
10
8
6
0
20
40
60
80
100
120
140
160
180
200
Distance (m)


MISSABOTTI CREEK 100m U/S of HELLIWELLS ROAD
SECTION A-A 1964 SURVEY
1989
1964
Height (m)
12
10
8
6
4
2
0
20
40
60
80
100
120
140
160
Distance (m)

APPENDIX 10

DETAILED THERMOLUMINESCENCE ANALYSIS RESULTS

Specimen Number	Site Number	Site Plateau Region (°C)	Analysis Temp (°C)	Palaeodose (Grays)	K Content (% by AES)	Rb Content (ppm assumed)	Moisture Content (% by weight)	Specific Activity (Bq/kg U + Th)	Cosmic Contribution (µGy/yr assumed)	Annual Radiation Dose (µGy/yr)	TL Age (ka)
W2349	D3	325-500	375	55.2±5.8	0.45±0.005	50±25	6.4±3.0	23.0±0.7	150±50	1038±48	53.2±6.1
W2350	D3	300-500	375	62.6±5.0	1.00±0.005	100±25	85.5±2.6	150±50	2457±52	25.5±2.1	25.5±2.1
W2351	N6	275-425	375	53.3±6.9	1.65±0.005	100±25	7.9±3	80.1±2.5	150±50	3288±57	16.2±2.1
W2352	T4	275-500	375	168±37	1.40±0.005	100±25	6.3±3	91.4±2.7	150±50	3310±60	50.9±11.2
W2718	T4	300-500	375	174±17	1.50±0.05	100±25	17.8±3	101±3	140±25	3184±60	54.6±5.4
W2719	T4	300-500	375	181±15	1.90±0.05	100±25	21.0±3	103±3	81±15	3424±56	52.9±4.5
W2720	T9	300-500	375	43.4±3.7	1.55±0.05	100±25	23.3±3	86.7±2.6	122±25	2820±56	15.4±1.3
W2721	T9	325-500	375	43.3±3.3	1.60±0.05	100±25	22.3±3	71.2±2.2	87±15	2610±51	16.6±1.3
W2722	N6	325-450	375	56.9±12	1.30±0.05	100±25	17.3±3	86.7±2.6	81±15	2727±57	20.9±4.4
W2724	N3	300-500	375	68.6±12.7	1.80±0.05	100±25	19.5±3	110±3	110±20	3528±62	19.5±3.6
W2725	N3	300-500	375	55.3±3.8	1.80±0.05	100±25	19.3±3	103±3	81±15	3384±58	16.4±1.2
W2726	S5	325-500	375	35.8±2.4	0.90±0.05	100±25	17.3±3	54.3±1.5	125±25	1851±53	19.3±1.4
W2727	D3	300-500	375	78.2±6.6	0.80±0.05	100±25	8.7±3	67.3±2.1	122±25	2164±61	36.1±3.2
W2728	D3	300-500	375	78.1±7.5	1.05±0.05	100±25	22.8±3	93.6±2.8	122±25	2521±57	31.0±3.0
W2729	W2	stepped	325	17.5±1.3	0.55±0.05	100±25	12.4±3	45.4±1.4	185±25	1517±55	11.6±0.9
W2730	W2	stepped	325	20.8±1.7	0.65±0.05	100±25	17.2±3	55.5±1.5	110±20	1648±51	12.6±1.1
W2731	W3	300-500	375	35.6±2.7	0.95±0.05	100±25	20.3±3	100±3	185±25	2656±59	13.4±1.1
W2732	W3	300-500	375	115±9	0.60±0.05	100±25	16.7±3	48.3±1.4	110±20	1476±51	78.1±6.5

Appendix 10: Detailed Thermoluminescence Analysis Result