Nambucca Valley River and Catchment Management Study

Technical Report D
Riparian Vegetation and Related Issues

December 1999

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1 Report Brief

This report is part of a series outlining the processes operating on the streams of the Nambucca Valley. These scientific studies have arisen due to the allocation of National Landcare Program funds by the Nambucca Valley Total Catchment Management Committee to Lyall Macoun Consulting Engineers and to the University of Wollongong School of Geosciences, in order to undertake the Nambucca River and Catchment Management Study.

The need to study the streams of the catchment in scientific detail has arisen due to widespread acknowledgement of a system in serious disrepair. Debate over remedial measures in conjunction with differing views on the causes of instability over the past 50 years, has shown further the need to carry out scientific study to establish facts about the river system.

This report, entitled "Nambucca Valley River and Catchment Management Study, Working Paper 6: Riparian Vegetation and Related Issues" is intended to review the historical and present character of riparian vegetation in the Nambucca River Catchment, and in particular to focus on its geomorphic significance and possible use for remedial work to control fluvial erosion.

The specific issues outlined by the management committee to be addressed in this report include:

All issues relating to the role of stream bank erosion processes which are included in the overall brief
The effect of human activity on riparian vegetation and thereby the stability of the channel and banks
The effect of other human activities (eg. Stock access) on bank stability
Guidelines for river bank vegetation management to achieve long term stabilisation

These objectives are, in large part, the objectives for the entire project, and as such it is somewhat ambitious to expect that conclusive 'answers' to these issues can come from an investigation of riparian vegetation which forms only part of the overall study.

For the purposes of this report, riparian vegetation is defined as the vegetation in river channels, on river banks, and on flood plains subject to inundation by flood waters.

The role of riparian vegetation as an agent affecting the behaviour of river channels within the Nambucca Valley, needs to be incorporated into all components of this project. Nevertheless, all attempts have been made to address the issues put forward for investigation by the Catchment Management Committee in the most appropriate manner given the considerable time and financial constraints of the project.

Because riparian vegetation must be considered in the context of other geomorphic factors, certain aspects of this report will be repeated in more detail in later reports. In particular, issue relating to river instability, channel incision and planform changes will be re-examined.

An evaluation of river stabilisation schemes was to have been included in this report. However, assessing such schemes requires an understanding of the local sedimentology, geomorphology and geotechnical characteristics of the banks, as well as the vegetation. Such an assessment will therefore be undertaken as a separate report, once these other issues have been addressed.

A number of reports have already been written about aspects of riparian vegetation within the Nambucca Valley, highlighting both its beneficial and detrimental roles in river management. It is not the intention of this working paper to repeat the work contained within these reports. Rather, these reports will be reviewed and where appropriate they will be added to.

Previous reports assessed include:

- L.A.W.C. (1996) "Progress report for Nambucca River restoration works - August - May 1996"
- D.W.R. (1995) "Nambucca River restoration program"
- Raine, A. (1994) "Use and management of native vegetation for river bank stabilisation and ecological sustainability. DWR Report NDW1.
- Thoms, M.C. (1994) "Bank erosion and sand and gravel extraction in the Nambucca River and Missabotti Creek". Report to NSW DWR.
- Resource Planning Pty Ltd (1989) "Nambucca River and Missabotti Creek channel stability and gravel resources". Report to DWR.
- W.R.C. (1979) "River improvement branch - Nambucca River investigation".
- P.W.D. (1974) "Flood mitigation works required in the Nambucca River Area".
- W.C.&I.C. (1971) "River improvement works within Nambucca Shire".
- + various Landcare submissions etc.

Landowner surveys (appropriate comments contained in Appendix 2), and conversations with landowners, members of the TCM committee, and other interested parties, as well s some of the material contained within the reports mentioned above, have highlighted a number of misconceptions surrounding the role of vegetation within the streams of the Nambucca Valley. The major contentious issues appear to be:

- River oaks (*Casuarina cunninghamiana*) - Friend or foe?
- Willows (*Salix spp.)* - Godsend or future nightmare?
- Native riparian vegetation - What species should be utilised for river stabilisation?
- Woody debris - Where has it gone? How do we get it back? What use is it?
- Where will revegetation work and where won't it?
- Stock exclusion and riparian buffer strips - Is this the answer?

To address these points, plus the problem of how best to incorporate the riparian vegetation issue into the other components of the overall project, we have decided that what is most needed at this point in the management process, is an overview of the theoretical basis underpinning the various ways in which riparian vegetation affects river processes, explained within the context of historical land-use in the Nambucca Valley. It is only with a sound understanding of the role played by riparian vegetation that most of these management issues can be addressed. Such an assessment has been missing from nearly all previous reports addressing the use of vegetation as a management tool. Raine (1994) is the exception, as he included a fairly brief overview of some of the relevant geomorphic literature in the introduction to his report on the use of native riparian vegetation for river bank stabilisation, and hence this report builds on Raine's overview.

In addressing the theoretical aspects of vegetation as a control on river behaviour, there will necessarily be some repetition of theory presented in other working papers.

Following a review of the basic principles of vegetation and alluvial river interaction, a range of theoretical issues will be discussed, as they specifically relate to the Nambucca catchment. Issues covered will include:

- Problems of catchment scale. ie. How do river/vegetation interactions change as you move downstream (or increase catchment area)?
- Long term river evolution in the context of pre-European riparian vegetation.
- The impacts of European land-use on riparian vegetation and associated changes to river behaviour.
- Variations in the role of vegetation between the various arms (tributaries) of the Nambucca system.
- Vegetation changes over the last 50 years, and perceived associations with river degradation.
- The role of vegetation within an unstable alluvial system.

Having considered these theoretical aspects of the Nambucca valley, specific management issues will be addressed.

2 Principles of Alluvial River Behaviour

2.1 Introduction

2.1.1 Rationale for Theoretical Approach

The question might be asked - Why bother with theory? Isn't it just text book nonsense for those who have never lived here and don't have a clue about what is going on with our river?......

A vast body of scientific literature has accumulated in Australia and overseas which has investigated both theoretical and field based aspects of river behaviour and river degradation. The degradation and behaviour of streams within the Nambucca Valley, as anywhere, are constrained by a set of fundamental physical principles. Whilst there is a unique combination of geologic, physiographic, climatic, hydrologic and ecological constraints which have led to the evolution of the streams we see in Nambucca today, the underlying principles governing the behaviour of these streams is the same here as anywhere. As such, much can be learnt about the way Nambucca River and its tributaries are behaving by going back to the first principles of how rivers operate, and also by learning from examples elsewhere. As outlined in the brief, it is apparent that in the studies already written about the Nambucca Valley, this "first principles" context is conspicuously absent, particularly with respect to riparian vegetation. For this reason the following section briefly reviews what is known about the effect of vegetation on rivers, as well as providing a simplified version of the fundamental constraints dictating river behaviour and where vegetation fits into these constraints.

This analysis then forms the basic building blocks for assessing the role currently being performed by riparian vegetation, particularly including the variation between tributaries, and between different sections of each tributary.

2.1.2 Inter-Tributary Variability and Broad Scale Catchment Geomorphology

Understanding inter-tributary variation in broadscale geomorphic controls is fundamental to understanding the erosion and bed-load transport processes in each tributary. This report will demonstrate that understanding such variability in catchment scale controls is crucial for understanding the effect of vegetation in each tributary. For example, sediment supply (bed-load transport) is controlled by the geology within each tributary, the slope of the catchment, the degree of valley confinement, and the location and character of stored sediment deposits which may be being reworked by the contemporary river. The nature of alluvial storage units in different parts of each tributary dictates the bank erosion processes which will dominate at each location, and hence how vegetation is likely to act as an erosion control. In many river catchments there can be considerable variation in the nature of these broader scale controls between the various tributaries. The tributaries within the Nambucca Valley exhibit considerable variability, and this must be taken into consideration when deriving appropriate management strategies. That is, no uniform solution exists that can be applied across the entire catchment. Different strategies will need to be employed in different parts of the system, and the goals at each site will need to be integrated into a universally agreed long term management goal for the rehabilitation of the whole system.

2.1.3 The Importance of a Historical Perspective

The other crucial element in deriving the "right" management strategy, particularly where vegetation is concerned, is determining the nature of the current instability within the river system - what happened in the past, and what triggered the instability. From the previously published reports, it is apparent that no one has come to terms with exactly what happened to the Nambucca system. The clearance of riparian vegetation and the 1950s floods have been blamed, but the evidence for these two causes has not been convincingly presented. Until we understand what happened and why the extent of destabilisation is different from tributary to tributary, any management strategy is likely to fail. Furthermore, it is not possible to determine what vegetation is currently doing in the various tributaries, or to make any conclusive predictions about the likely future role vegetation might play in system rehabilitation without this understanding. From the reports reviewed (eg. D.W.R., 1995) it is clear that many management strategies employed to date are at worst, treating the symptoms without even knowing what the illness is, and at best, addressing a specific problem without any regard or understanding of the implications to the rest of the system.

Just as failure to understand the primary causes of river instability will lead management strategies to failure, so too will a failure to learn from the collective wisdom embodied within the scientific literature on river behaviour. If a healthy river is to be re-established, this must include a combination of perspectives from the engineering, geomorphic and ultimately ecological literature.

2.2 Primary Controls on River Channel Morphology

2.2.1 Applications of a modelling approach

Before assessing the aspects of river geomorphology and flow hydraulics affected by riparian vegetation, we must first briefly review the complete array of theoretical constraints on an ideal river channel.

The shape, size and behaviour of 'stable' river channels is dependent on the complex interaction of a substantial number of variables, all of which can be described mathematically, and their inter-relatedness at least partially explained mathematically. It is beyond the scope of this report to go into the complex modelling required to explain channel functioning, however, a simplified version of the general principles is appropriate. The theory assumes you are dealing with a true alluvial channel, one which is flowing over unconsolidated alluvium and is therefore capable of modifying its own bed and banks.

2.2.2 Static and Dynamic Models

The majority of models developed to date are static models which are only capable of modelling the channel condition at a single point in time, given a set of controlling variables (Darby & Thorne, 1996). Such models assume stable channel geometry has been maintained over an appropriate time scale (engineering time scales of around 100 years are the most appropriate in this case). This means that provided the controlling variables remain roughly consistent over this time-frame, a channel will have adopted a mean dimension, although it will have fluctuated to varying degrees about this mean condition. Paradoxically, a stable channel commonly has eroding banks, for a stable geometry refers to the mean channel dimensions over a given time-frame. A channel undergoing bed degradation and expansion, or conversely channel contraction, is not considered stable. However, a river laterally migrating across its flood plain is considered stable, as long as the channel maintains roughly constant dimensions. The model does not include valley confinement, an important constraint in many NSW coastal rivers.

A channel that has experienced major perturbation over the appropriate time-frame (eg. engineering time in this case), can't be considered stable, and must therefore be explained using a dynamic model. Dynamic models introduce an additional layer of complexity, and will have a different set of controlling and dependent variables.

2.2.3 Static Model Variables

The controlling or *independent variables* for a stable system (*after* Millar & Quick, in press) are:

- $\mathbf{Q_{bf}}$ - Bankfull discharge. This is assumed to be the flow that does the most 'work' in shaping the channel. It is assumed to correspond to the flow having a recurrence interval of around 1.58 years on the annual series
- $\mathbf{G_{bf}}$ - The sediment transport rate at bankfull discharge
- **d** - Grain size characteristics ($\mathbf{d_{50}}$, $\mathbf{d_{35}}$, or some other appropriate measure of the grain size)
- k_s - The equivalent roughness height (partly a function of the grain size)
- *c* - Mean bank cohesion. This is a function of the grain size of the bank material

- ϕ - Mean bank material friction angle (ie. the angle of internal friction or angle of repose, which is fixed for a given grain size)
- γ_t - Unit weight of bank substrate
- τ_{crit} - Critical shear strength for the bank substrate (ie. = shear stress at point of bank failure)
- S_v - Valley slope is assumed to be constant over the engineering time scale being applied to this analysis

Values of a number of constants are assumed. These are: gravitational acceleration g (9.8 m/s^2), density of water ρ (1000kg/m^3), specific gravity of the bed sediments s (2.65), kinematic viscosity ν (1x10^{-6} m^2/s), unit weight of water γ (9810 N/m^3)

The *dependent variables* (ie. those which are free to adjust and form an optimum channel condition within the constraints imposed by the interaction of all other variables) are as follows:

- P_{bed} - Mean bed wetted perimeter }
- P_{bank} - Bank wetted perimeter } often combined, but Millar & Quick (in press) separate them.
- S - Channel slope
- θ - bank angle
- f -friction factor
- U - Mean velocity
- R_h - Hydraulic radius (w x d/total wetted perimeter)
- W - surface width
- Y - bankfull flow depth (= bank height)

2.2.4 Dynamic Model Variables

Under dynamic conditions a number of the variables that were considered independent for the static condition, become dependent variables. All the variables that are dependent for the static condition are dependent for the dynamic condition. The additional dependent variables are:

- Q_{bf} - Bankfull discharge
- G_{bf} - The sediment transport rate at bankfull discharge
- **d** - Grain size characteristics
- k_s - The equivalent roughness height

In addition, Millar & Quick (in press), use a modified friction angle (ϕ) which is a function of the bank vegetation. Under dynamic conditions this also will become a dependent variable, given that the vegetation is subject to change over the engineering time-frame being considered.

2.2.5 Significance of Modelling

For at least the last 100 years, engineers and geomorphologists have been refining relationships that model the way these variables interact, and hence providing quantitative insight into the way natural rivers behave. Mathematical equations have been formulated to try to represent the interactions between these variables, assuming that enough of the independent variables are known. There are a now a range of models available which give various interpretations of how the variables interact and none of the models are perfect, but they can nevertheless help river managers to understand the likely outcome of manipulating some of the variables. In this report we will use as a guide a recent optimisation model developed by Millar and Quick (1993; in press). Whilst we will not go into the mathematical detail of the model, we can use this as a starting point to highlight which of these variables it is possible to manipulate through vegetation management. However, it must be recognised that the time-frame over which some of these manipulations will take to have a gross effect on a river like the Nambucca and its tributaries, is decades, if not centuries.

2.3 VEGETATION AND MODEL VARIABLES

2.3.1 Dependent Variables in the Nambucca System

Over engineering time scales (ie. around 100 years) the Nambucca system clearly has undergone major channel adjustments, and is still highly unstable. As will be detailed in Section 4.3, the channel has incised considerably in some places, widening, and increasing its bed-load supply by encroaching into stored flood plain deposits. As such, the variables over which vegetation can exert some control are those defined as dependent variables in the dynamic situation. Eg:

Channel Dimmensional characteristics:
- P_{bed} - Mean bed wetted perimeter }
- P_{bank} - Bank wetted perimeter } often combined, but Millar & Quick (in press) separate them.
- W - surface width
- Y - bankfull flow depth (= bank height)
- θ - bank angle
- R_h - Hydraulic radius (w x d/total wetted perimeter)
- S - Channel slope

Hydraulic Characteristics:
- f -friction factor
- U - Mean velocity
- Q_{bf} - Bankfull discharge.

Sediment Characteristics:
- G_{bf} - The sediment transport rate at bankfull discharge
- **d** - Grain size characteristics
- k_s - The equivalent roughness height

General Constraints:
- (ϕ) - modified friction angle

Due to the large number of inter-related variables, it is not possible to assign direct cause and effect between one variable and another. Both positive and negative feedbacks are working between the variables, often on different time scales, and to varying degrees. In addition there will be considerable variation in the weight of each variable under different sets of circumstances.

If we assume that the ideal management objective is to achieve a river channel that is relatively stable, where bank erosion and bed-load transport is minimised, it is perhaps best to look at the likely direction of change to each variable associated with different vegetation treatments. We will simplify the dimensional parameters to just width, depth, bank angle and channel slope.

As will be shown in the following review, channels having dense vegetation tend to be significantly narrower and to a lesser extent deeper than the same channel would be in the absence of vegetation. Channel slope also tends to be lower in rivers with well vegetated riparian zones (ie. slope is a direct measure of sinuosity in this case, given that valley slope is constant). Maximum slope is generally when the channel length and the valley length are the same. It is possible to have a channel that is steeper than the valley slope, when the upper part of a straight reach is aggrading more than the lower section.

Of the other dependent variables, friction factor can be separated into 4 sub-components - the grain, bed-form, bend and vegetation components (of which the vegetation can be divided into woody debris and living vegetation). Flow resistance (friction factor) can be significantly increased and mean velocity reduced by riparian vegetation and woody debris.

The sediment characteristics, particularly bed-load transport, can be indirectly reduced by vegetation through its influence on channel hydraulics (eg. increased flow resistance, and hence reduced velocity and bed shear-stress). In addition, vegetation can directly reduce bed-load transport rates by stabilising point bar and lateral bar deposits, which often act as temporary storage units for relatively mobile bed-load.

2.3.1.i Vegetation and Bank Friction Angle

Millar and Quick (1993; in press) utilise a modified friction angle to quantify the threshold angle of stability that a given bank material is capable of maintaining. This parameter includes both the angle of internal friction of the bank substrate and the additional component contributed by bank vegetation. Clearly, this parameter is subject to considerable changes within the engineering time-frame, and even greater variation over longer time scales, when the changes associated with riparian vegetation clearance are considered.

2.3.1.ii Vegetation and Flood Plain Material

Whilst it is true that over engineering time, all the variables related to bank material can be considered independent (ie. roughly constant over the last 50 years and the next 50 years) , over the time it took for them to be deposited, they are in fact a function of the conditions in the channel and on the flood plain. Hydraulic roughness associated with vegetation on the flood plain has been demonstrated to significantly influence the size fraction of sediments deposited (Nanson and Beach, 1977), and hence the bank friction angle, the shear strength of the bank material, and potentially even the valley slope. Flood plain vegetation has been fundamentally altered on all tributaries of the Nambucca and indeed all NSW coastal rivers (see Section 3.7). As such, the present flood-plain condition is out of phase with the conditions prevailing during the vast majority of its evolution. So, one of the primary aspects of the influence of vegetation on channel behaviour that must be considered is that associated with European clearance in the last 150 years.

2.3.2 Summary of Dependent Variables

The inter-relations between each of these variables and vegetation is best represented in table presents a qualitative indicator (low, med, high) of the potential for vegetation to variable, in either the positive or negative direction (negative means the value of the reduced, and positive means it is increased). Quantitative measures can't be given, due gross variation in baseline conditions at specific sites. To do this requires a complete sensiti analysis to be run through the model at each site. Scalar issues as discussed below also prevents absolute guidelines being produced for what vegetation will do in a river. This table is appropriate for a true alluvial river up to a couple of hundred km^2 in catchment area. In rivers significantly larger or smaller than this, or in unstable systems, some modification to these guidelines may be necessary. This table is a synthesis of much of the literature cited in the remainder of the report as well as the authors' experience.

	Bank/ch. vegetation		**Flood plain vegetation**		**Woody debris**	
	dense	***light***	***dense***	***light***	***dense***	***light***
Bed-load transport	mod -ve	low -ve	low -ve♣	low -ve	high -ve	mod -ve
Mod. friction angle	high +ve	low +ve	#	#	N/A	N/A
Friction factor (ch)	high +ve	low +ve	low +ve	low +ve	high +ve	mod +ve
Channel width	high -ve	low -ve	mod -ve♣	low -ve	mod -ve	low +ve
Channel depth	mod +ve	low +ve	mod+ve♣	low +ve	*	*
Slope	high -ve	low -ve	high-ve♣	low -ve	mod -ve	?
Flow velocity	high -ve	low -ve	mod -ve♣	low -ve	high -ve	mod -ve

Table 1 **Variables within the fluvial system subject to influence by vegetation**

* The effect of woody debris on bed level it is to create greater variability between pools and riffles - hence the mean condition may not be greatly different with or without LWD.

\# The effect of vegetation on friction angle is to increase the threshold angle of stability of a bank, and technically this only relates to the vegetation on the bank and in the zone immediately adjacent to the bank where root strength has an influence on the banks. However, if a channel is migrating, and the immediate bank vegetation is lost, the floodplain vegetation then comes directly into contact with the channel. Under these circumstance it can increase bank friction angle, depending on the bank height and root depth of the vegetation.

♣ The effect of flood plain vegetation is generally only realised in floods greater than bank full, or where channels are actively migrating.

? The effect of light vegetation on channel slope is probably negligible, but not enough information is available to confirm this.

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3 Literature Review

3.1 Introduction

Riparian vegetation plays an important role in many aspects of river evolution and contemporary behaviour. The nature of bank and flood plain vegetation throughout the Holocene (last 10 000yrs) is one of the factors dictating how the flood plain formed throughout this period. 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. Bank strength is significantly increased by well vegetated banks, such that channels having dense and well structured bank vegetation may be significantly narrower than the same channel without vegetation. The extent and nature of vegetation control on flow resistance and bank strength also varies with catchment scale. In addition, riparian lands with their fertile alluvial soils, were the first areas to be cleared and intensively farmed by early settlers (Brierley et. al. 1995). As such, riparian vegetation bore the brunt of early settlement, fundamentally altering the nature of the vegetation variable as a control on the fluvial system. The following literature review provides an overview of what is known about the role of vegetation in relation to each of the points outlined above.

3.2 The Extent of Riparian Vegetation Control in Rivers

3.2.1 Early Observations

The importance of riparian vegetation as an agent in bank stabilisation (ie. the implications of removal) were first recognised in Australia by Governor King in 1803. An excerpt from The Sydney Gazette (cited in Raine & Gardiner, 1994, p.15), highlights the perceived problem with the removal of 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 clearly not scientifically admissible evidence for the role of vegetation in bank stabilisation, it provides supporting 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.

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

3.2.2 The Scientific Evidence

Vegetation is now known to exert a significant control on the size and shape of river channels. Empirical studies have shown that channels with dense bank vegetation (ie. trees and shrubs) will on average be between 0.5 - 0.7 times the width of an equivalent channel only vegetated by grass (Charlton et. al. 1978; Hey & Thorne, 1983; 1984). More recent theoretical modelling, which includes the vegetation variable in the derivation of a model of alluvial river behaviour from first principles, provides confirmation of the previously published empirical relationships - suggesting rivers with densely vegetated banks may only be 0.3 times the width (Ikeda & Izumi, 1990; Millar & Quick, 1993; 1996; Millar & Quick, in press).

In extremely simplified terms, what these studies are highlighting is the significant role of vegetation as a mechanism for increasing bank strength. There are a number of additional studies which confirm bank strength as the key mechanism by which vegetation exerts its control on a river. In a study of the effect of vegetation in a low order glacial meltwater stream, Smith (1976)demonstrated that herbaceous plant roots can increase the bank strength by 20000 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 (ie. a wide, multi-thread channel) where the banks and flood plain 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 USA a number of studies document strong associations between channel narrowing and invasion by *Tamarisk,* an exotic vegetation species, to river systems formerly having minimal 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 & Brierley (in press), demonstrated channel contraction of up to 50% in the lower Bega River over a 30 year period, 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. First, that changes in vegetation composition and structure can fundamentally change river behaviour. Second, that channel change associated with vegetation removal will not be inversely proportional to channel change following vegetation introduction. Third, 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 change that system to a single thread meandering channel (*sensu*, Nevins, 1969). Channel contraction must also occur, and for this to occur the vegetation must by capable of colonising within the channel. In so doing the vegetation has the potential to significantly influence a number of other fluvial processes. It will stabilise in-channel sediment deposits, it may induce wash-load deposition (ie. fine sediment that would otherwise not be deposited), and it can potentially reduce flow velocities. Each of these processes will subsequently be addressed, however, before doing so, a more fundamental 'problem' must be addressed.

3.3 The Scale Problem

The nature of vegetation's control on rivers and streams varies greatly with the scale of the catchment or, the potential discharge. The varying importance of vegetation as a control on channels at different catchment scales was first raised by Zimmerman et. al. (1967), who suggested that in very small catchments (up to about 2 km^2) grass and sedge dominated channels were smaller than channels having similar catchment area (or discharge) that were dominated by trees. However, moving downstream (ie. increasing the catchment area) channels dominated by trees became comparatively smaller than channels having equivalent catchment area but only grass and sedge on the banks and flood plain. Subsequent authors have acknowledged similar patterns elsewhere (eg. Gregory and Gurnell, 1988; Thorne, 1990; Abernathy & Rutherfurd , 1996), whilst Miller and Quick (1993; 1996; in press) acknowledge the phenomenon from a theoretical perspective.

Gregory and Gurnell (1988), working in British streams, explain the phenomenon by suggesting that two thresholds of catchment scale are operating (within their experience). They suggest channels with catchment areas less than $2km^2$ are dominated by non-fluvial processes, and whilst vegetation may dominate their morphology, they can't really be considered as true alluvial channels. They do, however, address Zimmerman at. al's. (1967) observations about low order grass and sedge lined channels, explaining that grass sod behaves more like a cohesive bank than do tree roots - hence the narrower channels under grass at this scale of catchment. Gregory and Gurnell go on to explain that in catchments up to a certain scale, which they suggest is $15km^2$, channels will be dominated by vegetation (without differentiating between vegetation type), and as catchment scale increases beyond this the relative influence of vegetation diminishes.

More cogent explanations are given by Millar and Quick (1993; 1996; in press), and Abernathy and Rutherfurd (1996) who approach the scalar problem from a more theoretical perspective. Millar and

Quick (1993; 1996; in press) citing the work of Grissinger (1982) and Thorne (1982) stress the importance of understanding the nature of the erosion processes operating within different parts of catchments before the role of vegetation at different sites can be understood. They demonstrate that, despite a myriad of bank erosion styles having been identified (see Murn, 1995, and Raine & Gardiner, 1994), there are effectively only two bank erosion processes, dictated by the geomechanical conditions of the bank.

Low banks that are below the critical height of failure (see Section 3.3.1for a detailed discussion of how critical height is determined) are dominated by fluvial corrasion, which is the removal of individual sediment particles or aggregates by moving water. High banks, which have a height greater than the critical height, are subject to mass failure. Mass failure occurs when the downward force associated with the saturated bank substrate, exceeds the resisting force associated with cohesion and internal friction of the substrate (Millar & Quick, 1996; p.235). In its most extreme form this involves deep seated slump block failure, which generally occurs during draw-down following a flood. In many rivers (although by no means all rivers) the upper reaches of the channel network tend to have low banks, and hence the dominant erosion process is corrasion, whereas the middle and/or lower reaches tend to be constrained by high banks which are dominated by mass failure. In between there will generally be a zone of varying length depending on the specific catchment conditions, where there is a combination of the two processes operating to varying degrees. It should also be noted that banks which are below the critical height, and which are therefore dominated by corrasion, can still be subject to slumping and block failure which may appear to be the same as mass failure. In this situation, the banks become undercut and then catastrophically fail, but the process causing the undercutting is corrasion.

Abernathy and Rutherfurd (1996) undertook a scalar analysis of the Latrobe River, in Gippsland, Victoria, in which they assessed the relative role of vegetation at different positions down the river. Their analysis largely confirms the theoretical predictions made by Millar & Quick (1993; 1996; in press), where they suggest the upper third of the total rivers length is dominated by corrasion , the middle reaches by mass failure, and the lower reaches by a combination of corrasion and mass failure. The fact that the lower reaches are less subject to mass failure than the middle reaches, is a common phenomenon in coastal rivers in Eastern Australia, where channel capacity decreases downstream as they emerge from escarpment foothills and cross the coastal plain (Nanson & Young, 1981; Woodfull et. al. 1996). Whilst Abernathy and Rutherfurd do not specify the catchment areas of the various reaches they delineated, it is clear that the catchment areas for the reaches in which they indicate a significant vegetation control are far in excess of that suggested by Gregory & Gurnell (1988) for British streams. Many of the previously cited studies on the impact of exotic vegetation in rivers also indicates rivers up to two orders of magnitude larger than the 15km^2 threshold suggested by Gregory and Gurnell may be profoundly influenced by the nature of the riparian vegetation. Work in progress by the primary author on the Thurra River, a fully forested alluvial system in East Gippsland Victoria, would also suggest that rivers at least up to 350km^2 can be profoundly influenced by vegetation.

A range of additional issues must be considered when assessing the relative influence of riparian vegetation at different catchment scales. Vegetation species composition must be considered in much greater detail than just grass, shrubs and varying forest densities as has tended to be the case in most studies to date (eg. Charlton et.al. 1978; Andrews, 1984; Hey & Thorne, 1983; 1984). This may seem obvious to the average landowner, but it has been ignored by many in the geomorphology and engineering professions. The most important consideration is relating rooting depth and structure of different species with the dominant bank erosion process at different sites, as well as different substrate conditions. Individuals of the same species can exhibit significantly different rooting structures depending on the nature of the substrate (pers. obs.).

The varying role of woody debris must also be considered in the context of channel and catchment scale relationships as the type and size of wood likely to be recruited to the channel changes in different parts of the catchment (see Section 3.6). The effect of vegetation on flow resistance also varies considerably with channel scale (see Section 3.4).

3.3.1 How to Assess Critical Bank Height

The method for establishing critical bank height and hence the dominant erosion process at a site is outlined in Millar and Quick (in press). The method uses a total stress analysis incorporating slope stability tables of the type published by Taylor (1948).

$$H_{crit} = \frac{c\,N_s}{\gamma_t}$$

where:

H_{crit} = critical bank height (m) corresponding to a factor of safety of 1.0

c = soil cohesion as estimated in the field using a shear vane. The analysis assumes soil friction angle = 0 (ie. the point of failure), and hence c = measured value (in N/m^2). The test must be carried out when bank material contains a high moisture content. This is because the test assumes maximum bank failure occurs at bank-full condition or during draw down following high flow when bank material is saturated.

N_s = a dimensionless stability number which can be estimated according to a piece-wise equation after Terzaghi, (1943 p.159):

$$N_s = \begin{cases} 3.85+0.045(90-\theta) & \theta > 53^\circ \\ 5.52+0.086(53-\theta) & 53^\circ \geq \theta \geq 30^\circ \\ 7.50+0.219(30-\theta) & \theta < 30^\circ \end{cases}$$

where θ is the measured bank angle

γ_t = bulk unit weight of bank material (N/m^3)

3.4 Flow Resistance

Vegetation within river channels can comprise a significant proportion of the channel roughness, or resistance to flow. Channel roughness causes energy dissipation and hence a reduction in the average flow velocity. Whilst average velocity will be reduced by within-channel vegetation, local velocity increase can occur in association with turbulence around a single tree or shrub. In simplistic terms, the hydraulic effect of vegetation is proportional to the area that is projected into the channel cross section at bankfull. As a general rule, the proportion of vegetation occupying the channel cross section decreases downstream (Abernathy & Rutherfurd, 1996). Clearly, this depends on the channel shape and associated vegetation distribution. For example, a channel with vegetation only on the banks will have a different relationship to a channel with vegetation both on the banks and in the channel.

A number of authors have highlighted the fact that there is not a linear relationship between hydraulic resistance due to vegetation, and flow stage (Li & Shen, 1973; Petryk & Bosmajian, 1975; Kouwen and Li, 1980). Kouwen and Li (1980) suggest this is in part due to variability in the flexural rigidity of the vegetation (ie. the extent to which trees or shrubs are bent over by high stage flows). This is exhibited in two ways - first, variation in the resistant characteristics of individual trees at different flow stages depending on the extent to which they are bent over (Petryk & Bosmajian, 1975). Second, variations in the rigidity of different species. Petryk & Bosmajian (1975), also highlight the fact that many species have a greater extent of foliage higher up the plant, and as result flow resistance will be greater at higher stage.

The fact that many river management agencies until recently (or in some cases still do) occupied a large proportion of their time clearing vegetation from channels as a flood mitigation measure (Rutherfurd et. al. subm), is testimony to the flow resistance role of vegetation. Measures of vegetation resistance (Manning's n, or the Darcy Weisbach friction factor f) have been obtained from measurements made before and after such channel clearance exercises (see for example Burkham, 1976; Masterman & Thorne, 1992). Burkham (1976) suggested total hydraulic resistance was reduced by 30% following vegetation clearance from the channel of the Gila River. Others have measured increases in Manning's n following vegetation incursions into channels. Petts (1984) gives the example of a sand bed river where Manning's n was increased from 0.036 to 0.2 following the colonisation of willows into a channel. Graeme and Dunkerley showed that in semi-arid ephemeral channels in the Barrier Ranges of western NSW, river red gums accounted for just under 50% of the total hydraulic resistance of these streams at high flow.

Due to the downstream reduction in relative influence of vegetation on total hydraulic resistance, it follows that the greatest impact of vegetation in reducing erosion by corrasion will be in lower order channels (ie. further upstream). Here, channel capacities are generally less, and the dominant bank erosion process is corrasion. This is not to say bank vegetation can't be significant in higher order channels. Boundary shear stress (the erosive force at the bank surface) is proportional to the square of the near bank velocity. As such, a minor reduction in the average velocity can cause a significant reduction in the shear stress responsible for corrasion (Abernathy & Rutherfurd, 1996, citing Ikeda et. al., 1981). A good vegetation cover on a bank which reduces the near bank flow velocity can greatly reduce total bank erosion, even if the reduction to total channel velocity is fairly minimal.

As demonstrated in Working Paper 4 (Bed-load Transport) total bed-load transport is highly susceptible to variations in Manning's n (flow resistance). Li & Shen (1973) demonstrated from flume studies that flow resistance associated with in-channel vegetation can reduce bed-load transport rates by more than 90%. As is clearly demonstrated through the clearance of vegetation from natural channels for flood mitigation, the manipulation of vegetation in a river is the only viable way to substantially increase Manning's n, and hence reduce bed-load transport. When the additional role of tree and shrub roots stabilising mid-channel bars, and point bars is considered (ie. one of the primary source areas for reworked bed-load), the overall potential for vegetation to minimise bed-load transport may be even more profound.

The work of Andrew's (1984) in gravel-bed streams in Colorado (and cited in Raine; 1994), presents an apparently contradictory interpretation of the relationship between bank vegetation and flow velocity. Andrew's concluded that, compared to channels with light bank vegetation, rivers with dense vegetation have similar depths, are 26% narrower, have higher velocities and on average are twice as steep. The key to understanding this contradiction lies first, with the scalar relationships discussed above, and secondly, with the relationship between channel slope and velocity (ie. there is a strong correlation between slope and velocity). For Andrew's conclusions to be generally applicable a causal relationship must be demonstrated between the slope of the streams surveyed and the bank vegetation. That is, the channels must be in equilibrium with the riparian vegetation. The majority of evidence from elsewhere suggests this is unlikely to be the case, as channels adjusted to a densely vegetated riparian zone almost invariably have higher sinuosities (lower slopes) than similar channels that have adjusted to a cleared riparian zone.

3.5 Root Reinforcement

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; in press) utilised 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 & 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, to impart the greatest strength characteristics on the bank.

An additional riparian vegetation root characteristic rarely considered by geomorphologists and river managers, is the role played by the roots of trees and shrubs contained within bank slump blocks. 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. 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.

3.6 Woody Debris

3.6.1 Introduction

The term woody debris is relatively self explanatory - it is in effect dead riparian vegetation that has fallen into a river channel. Large woody debris (LWD) is defined by various authors as organic debris larger than some specified minimum size (usually log diameter). A recent review by Gippel et.al. (1996) indicates a range of minimum sizes have been used, however, the most common seems to be 0.1m diameter. From a hydraulic perspective LWD in rivers performs a similar function to live vegetation. LWD can comprise a substantial proportion of total hydraulic resistance (eg. Manning's n), particularly in headwater reaches and relatively undisturbed lowland river reaches (Abernathy & Rutherfurd, 1996). However, in disturbed rivers, its role is substantially reduced due to long term efforts by management agencies to rid many rivers of its influence (Rutherfurd et. al., subm.). Over and above the hydraulic influence, LWD plays an additional role in bed stabilisation, or bed level control. The combined influence of these two factors means that in some streams the effect of LWD on overall channel morphology may be more significant than that of living vegetation. LWD also plays an extremely important ecological role in rivers, however, this report does not address this aspect.

3.6.2 LWD and Catchment Scale

As with live riparian vegetation (outlined above) the extent to which LWD affects flow resistance and bed stability in general, diminishes with increasing catchment scale. There are two reasons why this is the case. First, as with vegetation, a greater proportion of channel cross sectional area will be occupied by LWD in low order channels (Thorne 1990; Nakamura & Swanson, 1993; Abernathy & Rutherfurd, 1996). To some extent this relationship assumes that there is equivalent LWD recruitment throughout the system, which is rarely the case. In virtually all published studies that have looked at this relationship, human impact on LWD becomes more prevalent downstream (Cohen et. al. 1996). Hence nearly all LWD studies will be biased due to both removal of LWD in higher order channels, and reduced or negligible recruitment. Nevertheless, the relationship does still hold true for most rivers.

The second scalar change in the role of LWD downstream relates to the relative size of the debris compared to the size of the channel. In low order channels the height of trees falling into channels will generally be greater than channel width. In these circumstances the logs will often remain as they fall, and often for considerable periods of time. Residence times for such logs have been reported as 200 years for redwood logs in Oregon streams (Gregory & Gurnell, 1988), 700 years in British Colombian rivers, (Fetherston, et. al. 1995) or up to several thousand years for Huon pine logs in some Tasmanian streams (Nanson et. al ,1995). Very often the logs falling in low order streams are close to perpendicular to the flow, causing maximum blockage (or resistance) to the flow. An exception to this general rule is in the lowest order channels which may have steep bedrock slopes. In these circumstances logs may actually be held above the channel, having little or no effect on flows (Nakamura & Swanson, 1993). As channel width increases downstream the height of the recruitable riparian vegetation tends to be less than channel width. LWD, in these circumstances tends to get swept around, often almost parallel to the flow, where its blockage ratio becomes minimised, but its role in point bar accretion and bank toe protection is maximised (Nanson, 1980). In wider channels, there is also a greater potential for LWD to be transported beyond the fall point, and to become incorporated into log jams.

In middle and lower order channels the overall effect of substantial flow resistance and bed stabilisation will be to minimise bed-load transport and reduce the erosive power of flows, hence minimising bank erosion. This is not say localised erosion will not occur. Indeed, in heavily vegetated moderate sized rivers, a high proportion of lateral channel migration may be associated with either single large trees, or LWD jams (Keller & Swanson, 1979; pers. obs.). In larger channels the overall effect of LWD in reducing flow velocity may be minimal, as will the tendency to regulate bed stability. However, the toe stabilisation role of parallel debris may be critical for the maintenance of a stable channel.

3.6.3 LWD Longitudinal Distribution

Discrete log jams play an entirely different role to uniformly distributed LWD. Uniformly distributed LWD, as discussed, maximises hydraulic resistance and bed stabilisation. Studies in the Pacific North west of USA, have demonstrated that up to 80% of channel fall may be associated with LWD (Heede, 1972; Keller & Swanson, 1979; Gregory & Gurnell, 1988; Nakamura & Swanson, 1993). Log jams, on the other hand, tend to have profound influences at specific sites, but depending on their downstream frequency, may or may not have a significant influence on total flow resistance. Log jams can cause local bank erosion, and may even trigger channel avulsion or cutoffs (Nakamura & Swanson, 1993; Gregory and Gurnell, 1988). The situation where log jams will have the greatest effect on total channel morphology is where the backwater effects of successive jams impinge on the next jam upstream. Depending on the stability of the jams, in this situation flow resistance and bed level control will maximised.

Plate 1: *An example of LWD loads in a pristine alluvial river - Thurra River, East Gippsland Vic. at a catchment area of approx. 180km²*

3.6.4 LWD and Hydraulic Resistance

The hydraulic resistance of LWD varies in a non linear fashion with flow stage, as was discussed for vegetation in Section 3.4. Manning's *n* associated with LWD can be extremely high in low order channels, with values greater than 1 being recorded by Beven et. al. (1979) and Gregory et. al. (1985). Hydraulic resistance is proportional to the projected cross sectional area of debris within the channel cross section. Abernathy & Rutherfurd (1996) reported blockage ratios of up to 80% in the upland reaches of the Latrobe River, which dropped off fairly quickly to less than 10% within 50km of the catchment divide. Gippel et. al. (1996) suggest debris loadings for small streams (< 10 km^2) fall between 0.001 - 0.436 m^3m^{-2}.

3.7 Human Impacts on Coastal Rivers

At the outset of this report (Section 3.1) it was claimed that riparian vegetation bore the brunt of impacts associated with European land use practices, and by inference this impacted on the rivers and their behaviour over the next 150- 200 years. This comment must be put in context of what is currently known about river channel change and European land use in the geomorphic literature.

3.7.1 The Impact of European Land use - Conventional Wisdom

The extent to which European 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 geomorpholgy 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 & Bell, 1982; Erskine, 1986; Warner, 1987; Warner,1992; Warner, 1995). European clearance and riparian land use were seen to be contributing factors superimposed on this 'natural' instability (Erskine & 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 & DDRs) (Warner, 1987; Erskine & 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.

3.7.2 An Alternative View

The fact that there is extreme climatic variability in eastern Australia has been clearly demonstrated by Finlayson & 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 (ie. over the last few thousand years), has recently been questioned (Raine & Gardiner, 1994; Brooks & Brierley, 1997; Brooks & Brierley, in press). Brooks (1994) and Brooks and Brierley (in press), assumed that the FDR/DDR regimes existed, but found that massive sedimentation associated with European 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) raises serious questions as to the validity of 50 year alternating cycles from a statistical and climatological perspective. Kirkup et. al. (subm.) 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 1940s or early 1950s, 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 (in press), 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 since European settlement (eg. Pickup, 1976; Eyles, 1977; Henry, 1977; Erskine & Bell, 1982; Erskine, 1986;Prosser, 1991; Prosser et. al. 1994; Murn, 1995; Burston & Good, 1996; Brooks & Brierley, 1997). In many cases, such behaviour appears to be outside the realm of river behaviour over the previous 5000 - 6000 years as inferred from the sedimentologic record. (eg. Eyles, 1977; CSIRO, 1993; Prosser, 1991; Prosser et. al. 1994; Brooks & Brierley, 1997). This being the case, recent work has sought to reassess the extent to which European disturbance of catchments, in particular the riparian zone, have primed many rivers for dramatic changes in form and behaviour. Such changes have been termed river metamorphosis (Schumm, 1969; Erskine, 1986).

3.7.3 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 European settlement can be firmly established. To many this whole issue may seem entirely academic, reminiscent of a "black arm band view of history". That is, what is 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. Lagged responses well in excess of 100 years are a common phenomenon in geomorphology (Chappell, 1983). Indeed, as will be demonstrated in Section 4.3.3 and 4.3.4, lags of this order of magnitude have probably been in effect on the Nambucca. 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.

A number of factors currently lead us to believe that riparian vegetation removal probably played a much more significant role than previously envisaged in channel metamorphosis studies where climate forcing is explicitly or implicitly assumed to be pre-eminent.

i) Many studies that have investigated historic river channel change (ie. those which have occurred during the time when historic records are available) have assumed consistency in the relative importance of controls on the contemporary river and the river as it had evolved over the preceding millennia. For many rivers this is a false assumption (Section 3.7.2 para 2).
ii) These same studies attributed little significance to the role of riparian vegetation in channel form and dynamics (ie. this includes the role of woody debris). The failure to account for the role of vegetation is one of the prime reasons for the inconsistency in the relative importance of controls on pre- and post- European river conditions (Sections 3.2.2; 3.3; 3.4; 3.5; 3.6).
iii) Recent advances in analytical modelling have improved our understanding of the potential for vegetation to control channel morphology (Section 3.2.2).
iv) Serious questions have been raised in recent years regarding, both the existence of FDRs and DDRs in NSW rivers, or their supposed imprint on the fluvial landscape (Section 3.7.2).

Climate is still the ultimate force driving river changes under this revised model, after all without floods little can happen within a river. The primary difference is one of emphasis.

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.

3.7.4 The Potential for River Instability

Understanding the potential for instability is a crucial precursor to understanding the role of vegetation. Rutherfurd et. al. (subm.) 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 flood plain 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 & Quick (in press).

3.8 The Pre-European Riparian Vegetation of the Nambucca River

3.8.1 Evidence for Vegetation Composition on Other NSW Coastal Rivers

The most comprehensive review of the likely composition of 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 which indicate similarities between the nature of riparian vegetation on the Manning and Nambucca Rivers, as well as Taylors Arm (Raine & 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 extensive stands of 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: 122 cited in Raine & Gardiner, 1994, p.27).

Perhaps one of the most detailed descriptions of the riparian jungle 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 rain forest, 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 & Gardiner, 1994, p.29)

The existence of a cedar getting 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 getting was practised along every coastal river north of the Shoalhaven 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, 1987). 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 1840s, the Macleay from the early 1830s, the Clarence from 1835 until the mid 1850s, Paterson and Williams Rivers from the late 1830s, the Nambucca, from 1842, the Bellinger, from 1842 continuing to the 1870s, the Tweed River from the 1860s, and the headwaters of the Hunter in the late 1860s.

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, p16) accounts of the vegetation associated with cedar forest provides an even better feel for 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".

Whilst this account is based on Gaddes own experience in the first half of the twentieth century, and most likely describes the rain forest conditions further up the valleys due to most of the lowland rain forest having long been cleared at this time, similar conditions would appear to have prevailed in the lowlands.

3.8.2 Pre-European Riparian Vegetation in the Nambucca

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 us a reasonably good idea of what pre-European conditions were like along the banks and flood plain of the Nambucca and its tributaries.

Gaddes (1990) provides the best indication of the extent of rainforest vegetation along the Nambucca flood plain. 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. His observation is particularly pertinent for the way LWD behaves in Australian rivers compared with overseas, as the logs tend to sink to the bottom of the channel and become incorporated into the river bed.

3.8.2.i Other Evidence

Further evidence for the pre-existence of extensive rain forest 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 flood plain. Red cedar, rosewood (*Dysoxylum fraserianum*), Eucalypt and river oaks have all been found in this manner (R. McWilliam, pers. com.).

3.8.2.ii River Oaks

From the historical sources reviewed , only two references are made to the presence of oaks, both of which are from the Hunter. In one reference cited above, 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*).

Therefore, we can only infer the previous distribution and extent of river oaks within the Nambucca. 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. 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-European river regime - hence the current proliferation of river oaks (see Section 4.5). However, from time to time such conditions must have prevailed, to allow for the ongoing survival of river oaks.

The mono-cultural primary colonisation by river oaks evident today, 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. Plate 2 is a photograph taken in 1995 on the upper Tuross, demonstrating the sort of colonisation common within the Nambucca today (See Section 4.5 for a full discussion of the advantages and disadvantages of river oaks in ongoing river management).

Plate 2: *River Oak colonisation on the relatively pristine upper reachs of Tuross River*

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4 Riparian Vegetation and Channel Interactions in the Nambucca Valley

4.1 Long term evolution of Nambucca River in the context of pre-European riparian vegetation.

In keeping with the debate surrounding the extent to which European clearance of riparian lands subsequently affected the morphology and behaviour of coastal rivers (see Section 3.7), there is little consensus as to what the NSW coastal rivers were like before European settlement. In addition to the issues outlined in Section 3.7, there are a number of additional reasons why this is the case:

i) Few researchers have seriously considered the effect that post-settlement clearance of vegetation had on rivers.
ii) The detailed historical evidence does not exist, making it very difficult to make conclusive claims.
iii) The geomorphic evidence has often been destroyed in the subsequent river adjustments.
iv) The available geomorphic and sedimentological evidence is only now being collected and interpreted to provide an understanding of rates and processes.
v) Very few analogues of pristine alluvial rivers 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 an interpretation of the authors, and then only in general terms. This interpretation draws on a number of information sources:

a) The theoretical constraints already presented regarding the interactions between riparian vegetation and fluvial geomorphology.
b) The picture of the pre-existing vegetation structure established in Section 3.8
c) The personal experience of one of the first author's , of what is probably the last remaining alluvial coastal river in Eastern Australia outside the tropics which completely retains its original riparian vegetation cover and woody debris load. 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*, blue berry ash *Elaeocarpus reticulatis*, blackwood -*Acacia melanoxylon*, *Pittosporum undulatum*, *Notolea spp*. amongst many others, as well as many tree fern, ground fern and vine species.)
d) Observations from gravel and boulder streams in pristine rainforest in the North Queensland.
e) Historical data from before the 1950s can give some clues, however any evidence of channel condition after flood plain 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.

4.2 Pre-European Channel Condition

4.2.1 Initial Comments Regarding Woody Debris.

In general terms, there would have been significantly higher volumes of LWD in the pre-existing channels of the Nambucca Valley, than the current channels. Because of the smaller channel capacities prior to European disturbance (see Section 4.3), 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 more specific comments regarding the likely compostion of LWD in the Nambucca catchment:

- The longer term species composition of woody debris will be strongly biased towards species that do nott readily decay once they fall into the river. In the Nambucca the most resilient species would appear to be: Red Cedar, Rosewood, Eucalypt spp (most probably *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 windthrow.

- 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 - we just do not see examples of these timbers in the river today because there has been 150 years with virtually no new recruitment of large examples of these species.
- In addition, the only way this second group of species would be recruited to the stream was through bank erosion and because many of these species were very effective at minimising bank erosion, recruitment of such species was localised, and fairly slow. Consequently it was probably the windthrown trees that made up the largest component of woody debris. However, the other rain forest association species may have been locally significant.

4.2.2 Inferred Pre-European Channel Conditions in each Tributary

Detailed assessments of the likely pre-European condition of channels on a tributary by tributary basis are included in Appendix 2, in association with the air-photo evidence. The inferences made regarding the possible condition of the pre-European channel are a first approximation only, based on:

- historic accounts
- the 1942 airphotos
- what is known about the likely composition of the pre-European vegetation community
- the authors experience from elsewhere
- theoretical knowledge regarding vegetation interactions in rivers

A summary of the general pattern is as follows:

4.2.2.i Upper alluvial reaches Missabotti Creek (M1), North Arm (N1, N2), South Arm(S1, S2), and Taylors Arm (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 NorthArm 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.

4.2.2.ii Middle alluvial reaches Missabotti Creek (M2, M3), North Arm(N3), and South Arm(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 log jams 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 cutoffs locally more significant - ie. 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.

4.2.2.iii Lower alluvial reaches Missabotti Creek (M4) and North Arm (N4 - N6) and middle reaches of Taylors Arm(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 (ie. 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 hyadraulic 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 cutoffs locally significant -but not widespread.
- Local channel expansion and contraction probably more important here, possibly associated with log jams.
- Perennial flow - almost never ceased to flow.

4.2.2.iv Mid Buckra Bendinni Creek (B2)

- Low capacity channel separating large bedrock control scour pools.
- Bank erosion, corassion dominated.
- Rain forest vegetation may have encroached into the channel in the low capacity reaches between scour pools.
- The majority of woody debris would have been of windthrow 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.

4.2.2.v Lower Buckra Bendinni Creek (B3) and Lower South Arm (S5)

- Highly sinuous, well defined channel, meandering through a relatively broad flood plain.
- Lateral channel activity dominated by meander migration and cutoffs.
- Undercut banks may have been common, held up by dense rain forest 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.

4.2.2.vi Lower Taylors Arm (T9 - 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 (ie. 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/flood plain scour, particularly if catastrophic failure occurred.

4.2.2.vii Warrel Creek (including Eungai Ck) (W1 - W3) and Deep Creek (D1 - D3)

- Channel widths similar to the present condition.
- Bed level variation marginally higher (ie. deeper pools and possibly higher riffles).
- Woody debris levels higher, with a greater proportion of windthrown origin.
- Lateral channel instability fairly negligible, with the exception of some parts of lower Deep Creek where localised meander cutoffs may have occurred.

4.3 THE CAUSE OF RIVER INSTABILITY.

4.3.1 Information Base

A preliminary picture of the nature of change to the form and behaviour of Nambucca River and its tributaries has been compiled with the aid of a number of lines of evidence. Information sources drawn on include:

- Field investigation carried out by Brooks in April 1995 and February 1997
- Field investigation carried out by Nanson and Doyle throughout 1996 and early 1997
- Initial airphoto interpretation using the 1942, 1964 and 1991series
- Information provided from a landowner survey conducted by the consultancy team in 1996
- Theoretical knowledge of interactions between vegetation and fluvial geomorphology (reviewed in Section 2 and 3)
- The authors' understanding of human impacts on NSW coastal rivers (reviewed in Section 3.7)
- Evidence carefully selected from previously published reports (NB. much of this information was rejected)

Evidence of channel change gleaned from the airphotos was interpreted by drawing on the following evidence:

- Channel width - changes fairly obvious from the photos
- Sinuosity - cut-offs readily detectable
- Bed level lowering - this can be discerned using various lines of evidence:
  - i) visually using a stereoscope
  - ii) gully incision through small tributaries flowing across the flood plain is commonly associated with bed lowering of the trunk stream, (ie. secondary incision and nickpoint retreat up these tributaries in response to base level lowering of the trunk stream *after* Schumm et. al. 1984). These are readily discernible from the later airphotographs.
  - iii) In addition, channel widening generally follows the upstream migration of a nickpoint. If substantial channel widening is evident, starting at the bottom of a tributary and proceeding upstream, there is a good chance it is associated with the upstream migration of a nickpoint

- Pool in-filling - readily discernible from airphotos
- Bed-form homogenisation - ie. the removal (lowering) of riffles and in-filling of pools

Vegetation species level differentiation was rarely possibly, other than the identification of large river oaks or colonies of juvenile river oaks. Guesses can be made at certain locations as to the likely composition of dominant species, based on contemporary species composition.

Supplementary evidence to support observations made in this analysis is presented in Appendix 2, at representative sites throughout most of the tributaries. These plates show comparisons between the oldest and most recent airphotos available. Not all tributaries could be represented here due to the limited coverage of the 1942 photo series. It is acknowledged that the quality of these reproductions is poor - they have been included simply to provide supporting evidence for the claims made from detailed stereoscope interpretation. It is recommended that proper photographic enlargements be made of these sites as an education tool for the local community.

It should be stressed that these findings are preliminary only, and require more field investigation, and more thorough airphoto analysis. A detailed airphoto analysis is presented in Working Paper 5

4.3.2 River Instability

When discussing river instability it is important to remember that, even in their most pristine condition, alluvial rivers exhibit instability, in terms of lateral movement and bed degradation. The point was made frequently in Section 4.2, that when discussing the likely condition of the various channels prior to the arrival of Europeans, that lateral channel migration, expansion and channel avulsions were an integral part of the long term evolutionary history of these rivers and streams. The exception to this being the Warrell Creek tributary system in the south of the catchment, and Deep Creek to the north. Both these systems appear (in gross terms) to exhibit considerable long term lateral stability. Evidence presented in later reports will show that these channel systems have been laterally stable for thousands of years, and have flood plains which appear to be formed by vertical accretion. The following discussion does not include these systems, because they remain largely stable to this day (with the exception of the lowest site on Deep Creek).

Of the remaining tributaries there is considerable variation in the extent of instability. If one had to rank the tributaries in order of increasing stability, based on airphoto interpretation and field investigation (see Appendix 1), the order would be:

- Missabotti Creek
- North Arm
- Lower South Arm below the Buckra Bendinni Ck confluence and the lower few km of Buckra Bendinni Creek
- Middle Reaches of South Arm
- Middle Reaches of Taylors Arm
- Upper Buckra Bendinni
- Upper South Arm
- Upper Taylors Arm
- Lower Taylors Arm

Within this grouping there are a number of important differences in terms of the type and extent of instability. To understand these differences it is necessary to look at two things:

i) The differing broad scale geomorphic controls (eg. valley slope, bedrock control - ie. confinement and bed control, and geological variation).
ii) The historical sequence of events which led to the instability.

Broadscale geomorphic controls are dealt with elsewhere (Working Paper 4), so the remainder of this discussion will focus on the nature of processes driving the instability and their timing.

It is hypothesised that two phases of destabilisation have occurred within the catchment. The first probably occurred following European settlement, but definitely before 1942, although the exact timing can't be proven at this stage due to lack of baseline data on channel condition at the time of first settlement. The second phase is less equivocal, with sufficient historic and geomorphic evidence being available to test its timing and extent.

4.3.3 Phase 1 (1840s - 1940s)

The exact timing of the first phase is unclear at this stage. It clearly must have occurred prior to the 1940s, and most probably occurred in the decades following the first clearance of rain forest from the alluvial reaches of all streams. A series of large floods were recorded at Bowraville at the end of the nineteenth century (see Appendix 5), which may have been the driving force for this first stage in instability, although there could have been earlier floods not recorded. It would appear that in the middle reaches of many of the tributaries the entire cover of rainforest was cleared from the flood plain and the banks. In the post-European period prior to the 1940s some vegetation probably remained on the banks in the lower reaches, where the banks were higher and better graded.

The major impact of initial European clearance was therefore, felt within the middle and upper reaches of many of the tributaries, where significant channel expansion and associated bed level homogenisation took place (ie. lowering of riffles and in-filling of pools). Evidence for this expansion and an indication as to the extent of clearance, can be seen in the 1942 airphotos (see also Appendix 1&2). The primary cause of this channel expansion was the reduction in bank strength associated with vegetation removal, probably coupled with higher velocity flows following woody debris removal from the channels. Once the process began two positive feedbacks would have perpetuated the changes:

i) Further 'natural' removal of woody debris that was previously lodged in banks - ie. the logs became outflanked and were washed downstream as channel expansion took place.
ii) As the pools in-filled with the sediment released by channel expansion, bed form resistance would have reduced, further increasing channel velocities.

In gross terms this phase of destabilisation was far less significant than the later phase, however, it was important in terms of priming the channels to maximise disturbance associated with the next phase of destabilisation.

In keeping with the degree of later instability, the greatest extent of change occurring during this phase was experienced in the middle reaches of Missabotti Creek and to a lesser extent the middle and upper reaches of North Arm. The 1942 airphotos also indicate it 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 this is less clear.

In none of the tributaries is there any sign that this phase of instability released large volumes of gravel through to the lower reaches of any tributaries by the early 1940s. 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.

The dominant process operative during this Phase 1 period of destabilisation was corrasion, or fluvial erosion of banks seriously weakened by vegetation removal. The immediate response to bank strength reduction would have been channel expansion. Positive feedback associated with increased bed-load volume released from the banks, would have perpetuated the channel expansion (NB. - increased bed-load supply can alone cause channel expansion).

4.3.4 Phase 2 (Late 1940s - Present)

In contrast to the Phase 1 destabilisation, the second destabilisation phase was an entirely different process. Some time between the early 1940s and the early 1960s saw the beginning of a major phase of bed instability that continues to the present day in some tributaries.

Base level lowering and subsequent upstream nickpoint migration is evident throughout the entirety of Missabotti Creek and North Arm, the lower reaches of South Arm below Buckra Bendinni Ck confluence, and on lower Buckra Bendinni Creek upstream almost to site B3. In order to provide some context for the contemporary management issues in these tributaries, it is useful to trace the origin and progression of this bed level degradation.

The 1942 airphoto series indicate that bed degradation had not started on either North Arm and Missabotti Creek. Surprisingly, however, it had commenced on South Arm. The lower reaches of South Arm prior to the 1940s were highly sinuous. The airphotos show that a series of seven large meander cutoffs had occurred on the lower reaches of South Arm by 1942, immediately adjacent to and just upstream of Bowraville. Whether these cutoffs had been artificially induced, or were a natural response to some form of base level lowering below Bowraville (channel dredging for example) is unclear as yet. Nevertheless, substantial increase in channel gradient would have accompanied these 7 cutoffs, and it appears that significant bed lowering had occurred at that time as well. In 1942 North Arm can be clearly seen to be elevated above the incised South and Main Arm bed at the confluence. A process similar to that which initially occurred on lower South Arm, may indeed be currently underway at Site D3 on lower Deep Creek.

It would appear that at this time North Arm and subsequently Missabotti Creek, were primed and waiting for a flood or series of floods to trigger a nickpoint, or series of nickpoints, that would migrate rapidly upstream through these systems, causing bed degradation, and subsequent channel expansion which almost always follows bed degradation. The subsequent airphotos confirm this to have been the case. This base level derived bed lowering, transmitted throughout the system by nickpoint migration is the root cause of the grossly destabilised channel evident today in these two systems. There would appear to be ample anecdotal evidence for such bed lowering (see Appendix 3) and some documentary evidence (see Working Paper 4 and some of the data contained in Resource Planning Pty Ltd (1989)).

Whilst 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 bed-load in these two systems compared to South Arm. Nevertheless, nickpoints are gradually proceeding up South Arm, and are now well up 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 but not up South Arm itself.

4.3.5 Bed Lowering in Other Tributaries

While some landowners in middle reaches of Taylors Arm report bed lowering, it appears this is not due to wholesale nickpoint retreat migrating up through the whole of this system. Rather, any bed lowering on Taylors Arm, is of local origin, and not a systemic problem. The bedrock control of the bed level in lower Taylors Arm prevents such systemic nickpoint migration from occurring. A similar situation exists on South Arm (although not bedrock constrained), above Buckra Bendinni Creek, where some localised bed lowering is evident, however, it is not yet a systemic problem there either.

This evidence is no reason to argue that the *potential* for ongoing bed degradation doesn't exist in these channels. Even where downstream bedrock bars prevent the upstream migration of nickpoints triggered by base level lowering at the most downstream end of these channels, the continued evacuation of gravel from the bed in the middle and upstream reaches will eventually lead to serious bed lowering. Furthermore, the potential exists on South Arm for the upstream migration of nickpoints, now evident at the confluence with Buckra Bendinni Creek.

4.4 Management Implications of Bed Degradation

From a vegetation management and bank erosion process perspective, the implications of these nickpoints migrating upstream are profound. A number of relevant issue are outlined:

- The role of vegetation as a control on alluvial channel form and behaviour, as outlined in Sections 2 and 3, refer to stable channel conditions. When a channel is going through a major adjustment phase associated with bed degradation it is no longer considered to be behaving in a stable manner, and hence the theoretical relationships between in-channel processes and vegetation become much more complex, as outlined in Section 2.2.4.

- Bed degradation followed by channel expansion greatly increases channel capacity, and hence the proportion of flood flow contained within the channel. Stream powers under these conditions are probably higher than have ever been experienced during the evolutionary history of these streams.
- Gravel reworked from stored flood plain deposits has elevated local bed-load transport rates to levels unprecedented in the rivers evolutionary history.
- Channel expansion in an alluvial system almost always follows bed degradation. Under these conditions the vegetation may appear to be causing the bank erosion, but bank erosion would have proceeded irrespective of whether the vegetation was there. Indeed, in areas where the vegetation is of sufficient density, the overall rate of bank erosion is probably being slowed by the presence of the vegetation. The best analogue of this scenario available is Jones Creek in East Gippsland, a fully forested system which is experiencing a similar degree of channel instability to Nambucca associated with bed degradation. In this case the instability is associated with bed lowering on the Genoa River into which Jones Creek flows (Cohen, 1997.). One of the most interesting observations on Jones Creek, is that bank sections associated with trees, often tend to be protruding into the channel. That is, the trees are holding up the banks for longer than the grasses and herbaceous species. When they fall in they obviously do take a large piece of bank with them, but often the net effect of erosion associated with tree fall is to catch up with the erosion rate the rest of the bank is experiencing. A similar situation can be observed on parts of the Nambucca - see for example Site D3 on the lower reaches of Deep Creek (Plate 3).
- The dominant bank erosion process changes from what was probably corrasion dominance or an intermediate phase in which both corrasion and mass failure are important, to one dominated by mass failure as the channel incises and the banks increase in height.
- With increases in stream power and bed-load transport and with banks dominated by mass failure, the options for using vegetation as a management tool are greatly diminished compared to the situation before bed degradation.
- Until the bed degradation problem is dealt with, other management strategies will be very difficult, if not impossible to implement.

Plate 3: *Protruding tree roots in bank subject to mass failure associated with local bed degradation, Site D3 on Deep Creek*

4.5 Management Implications of Historical Channel Instability

A number of pertinent points can be taken from the identification of these two phase of instability that are relevant to the broader instability question and the broader aims of the project.

- The common perception amongst contemporary locals that little was wrong with the river before the 1950s cannot be sustained. It is true that the major phase of instability had not commenced by the 1950s, but the system had been primed and was ready to go, given suitable floods. Indeed, from airphoto evidence it is clear that significant local channel expansion was prevalent prior to the 1950s in the middle and upper reaches of many tributaries.
- The nickpoints have migrated through the entire length of Missabotti Creek and North Arm since the late 1940s, and stabilising this situation must be the priority objective of all management strategies. It is not enough to just address bank erosion. Vegetation based management strategies will only form part of the management strategy here. Major engineering works are probably required to initiate stabilisation in many locations.
- In some parts of these systems bed levels may have returned to something like their original average level, however, the pool and riffle or step-pool sequences have been largely destroyed. Consequently, this does not mean the bed instability problem is solved. It may only be a response to the transmission of a sediment slug moving down a channel.
- Any site specific management strategy must determine the nature of the dominant bank erosion process.
- Baselevel controlled nickpoints are still active in Buckra Bendinni Creek and potentially the whole of South Arm above Buckra Bendinni Creek. Whilst these systems are inherently more resilient than North Arm and Missabotti, they have the potential to do the same thing as these two systems. Preventing further upstream nickpoint migration must be considered a priority issue in these two systems.
- The convential wisdom in the local community that channel instability commenced on Taylors Arm after the 1970s red scheme clearance cannot be sustained, given the airphoto evidence presented in Appendix 1 & 2.
- The middle reaches of Taylors Arm have not experienced systemic bed degradation. Any bed degradation here is of local origin. The channel instability on Taylors Arm represents the continuation of Phase 1 style channel instability 50 years on, probably having been exacerbated by the 1970s channel clearance.
- Given the lack of systemic bed degradation in middle Taylors Arm, there is great potential for vegetation based management strategies in this area.

- Similarly, there is great potential for vegetation based management strategies in the middle and upper reaches of South Arm and Buckra Bendinni Creek, providing the nickpoint migration there is halted.
- Vegetation based management strategies will also be effective in the upper reaches of systems which have had nickpoints migrate through them, providing the depth of incision is not so extreme that banks are bank-height constrained. In most cases where banks are transitional, light engineering based strategies will be required as well.

4.6 VEGETATION CHANGES OVER THE LAST 50 YEARS - PERCEIVED ASSOCIATIONS WITH RIVER DEGRADATION.

Many long term residents of the Nambucca Valley have observed an increase in the extent of riparian vegetation over the 50 years, and at the same time have witnessed major increases in channel instability. Some have drawn the conclusion that increased riparian vegetation (which is predominantly river oaks) has caused the gross channel instability currently evident.

In Section 4.3 it was suggested that the underlying cause of river instability, particularly in North Arm and Missabotti Creek, is systemic bed degradation. In this section we will review the airphoto evidence for an increase in the extent of vegetation along all tributaries, and discuss the evidence for a causal relationship between vegetation build up and channel instability. The baseline data for this analysis is presented in Appendix 1.

4.6.1 Evidence for Increased Riparian Vegetation since 1950.

The airphoto evidence presented in Appendix 1 clearly supports 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. Airphoto interpretation, as outlined in the introduction to Appendix 1, doesn't allow us to determine the species composition, but it is a safe assumption that species composition in 1997 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 presented in Appendix 1 we can, on a tributary by tributary basis, draw the following conclusions on riparian vegetation changes between 1942 and 1991. It must be stressed that these observations represent gross changes. Where "discrete locations" are mentioned, this may be the river frontage for an entire property. If an individual land owner happens to live on one of these properties, he or she will, understandably, have a biased impression of what is a much broader set of 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 rain forest associations where exotic species like camphour laurel may have displaced native species.

For the general areas covered by mid, upper and lower reaches of each tributary see Appendix 1 and 6.

4.6.2 Riparian vegetation changes between 1942 - 1991

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 witout 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.

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).

Eungai Creek (W1).

Little change from the 1964 vegetation extent (1942 airphotos not available)

Lower Warrell Creek (W3).

Little change from the 1964 vegetation extent (1942 airphotos not available)

Middle Deep Creek (D2).

Little change from the 1964 vegetation extent (1942 airphotos not available)

Lower Deep Creek (D3).

As for middle Deep Ck. except for the unstable section at site D3, where vegetation is locally reduced.

4.6.3 Riparian Vegetation Changes and Channel Instability (or River oaks - Friend or Foe?)

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 the channel instability as outlined in Appendix 1 and Section 4.3. 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:

i) Between 1964 and 1991, the few kilometers 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 the channel instability, not the riparian vegetation.
ii) 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.
iii) At two of the most unstable sections of channel in the catchment, the flats around sites N3 and S3, channel instability has apparently increased at the same time that the extent of vegetation decreased. However, it must be said that the initial extent of vegetation (ie. 1942 condition) was not great at both these sites. Both sites have apparently been subject to extensive gravel extraction as well.
iv) On South Arm around the Buckra Bendinni Creek confluence, 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.
v) 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.

One could go on with further examples where the regrowth of riparian vegetation since 1942 does not correlate with channel instability in the same period.

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 1950s as has the Nambucca, without any deleterious impact on channel stability. The difference in these cases being that they weren't accompanied by systemic bed degradation. 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.

4.6.4 Hillslope Vegetation and Land Use Intensity

A further striking observation that can be made from the airphoto evidence is the quite profound increase in the extent of forest cover on many of the hillslopes, throughout most of the area surveyed. Of the three time-slices surveyed in the airphoto sets, it is apparent that the majority of this increase occurred after 1964 - very little change being observed between 1942 and 1964. The magnitude of this change is evident in many of the airphoto pairs presented in Appendix 2. A number of implications may can be drawn from this:

i) The intensity of farming in the valleys has apparently declined since the 1960s - indicating that the underlying cause of post 1950s river channel destabilisation is not related to increased farming intensity.

ii) It highlights the extent of pre-1950s clearance and the potential role of disturbance in the first half of the twentieth century, and probably the late nineteenth century, in priming the channels for major disturbance once the appropriate flood trigger was applied in the 1950s.

4.6.5 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 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 - ie. there has been a increase in habitat suitable for colonisation be such a species.
- It is our interpretation that the degree of instability we currently see in the Nambucca catchment would have been much the same had there been no river oaks in the system at all.
- That being said, river oaks should be seen as a species with many of the appropriate characteristics to aid river rehabilitation, if managed properly (see Section 4.8).
- For the causes of channel instability we must look to bed degradation as outlined in Section 4.3
- In channels subjected to major bed lowering associated with nickpoint retreat, bank erosion (ie. channel expansion), is an inevitable consequence. 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, overall 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.

4.7 WHERE WILL REVEGETATION WORK BE MOST EFFECTIVE?

As has already been alluded to, the use of riparian vegetation as a management tool will be most successful in river reaches not subject to bed degradation. Channel sections in which corrasion is still the dominant erosion process will respond best to bank and riparian buffer strip revegetation. The scope of this report did not allow a geotechnical assessment of banks in all tributaries to be undertaken to determine the relative nature of current bank erosion processes. A geotechnical assessment of bank condition will be undertaken following the procedure outlined in Section 3.3.1, and will be discussed in the final management plans.

Without having undertaken such an analysis, we can assume that other than in the upper most alluvial reaches of the various tributaries there are probably very few degraded river reaches where mass failure does not play at least a partial role. That is, most middle tributary reaches will be in transitional states, where both corrasion and mass failure are significant. Under these conditions, some form of engineered bank toe protection will be required, and this may be in addition to bed control measures at some sites.

The revegetation approaches outlined in Raine (1994) are most appropriate in these areas. As such there is no need for this report to go over this material again. In addition, there is already a good deal of experience within the local community about the use of the species outlined in Raine (1994) in these locations (e.g. the brush groyne works and revegetation on upper North Arm and Taylors Arm - see Plate 4). It is not within the scope of this report to evaluate these works, this will be done in Working Paper 7. So, beyond the geomorphic framework already outlined, there is little that can be added by the authors of this report to the collective wisdom of the people on the ground that have undertaken these works. Therefore, it is recommended that in these middle and upper reaches, direction be taken from those individuals with the on-the-ground experience of undertaking light engineering toe-revetment combined with riparian-zone revegetation.

Plate 4: *Apparently successful revegetation and brush groyne works on upper North Arm*

Without wanting to pre-empt the report reviewing the works already in place, in many respects it is probably too early to fully assess the success or otherwise of these works. Provided the banks at these sites are either transitional or sub-critical, bed-load transport is not excessive, and bed degradation is not excessive, these works should be successful.

It is well understood by those landcare groups involved with such revegetation projects, that in the first few years before the vegetation at such sites becomes well established, the vegetation is highly susceptible to flood damage. It should be stressed, however, that severe damage to a project incurred in the early years, does not necessarily mean that revegetation works will *always* fail at that site. It may be that the work was unlucky enough to experience a series of major flows immediately after the works went in.

4.7.1 Weed Management and Maintenance

As is widely recognised by those with experience in riparian revegetation, the success of any project does not just depend on a favourable period time with no major floods. Drought and extended moisture stress in new plantings can just as effectively destroy revegetation works as a major flood. Watering can prolong the life of juvenile plants during drought (providing the water can be carted from somewhere close by), but this will be time-consuming and not always possible.

Perhaps the greatest ongoing management problem that landowners can have some influence over, and hence improve the success rate of revegetation works, is the prevention of competition by weed growth. Minimising competition from weeds is crucial to the success of any revegetation program, particularly in the early stages. Manual weed suppression is the most ideal method, however, in many situations it is not going to be practical to undertake such a labour intensive management technique, particularly on larger holdings where land owners have many other priorities, and when larger scale revegetation works become more prevalent. Under these circumstances the only viable weed management option is going to the use of herbicides.

- Therefore, it is recommended that approval be sought to enable the use of glyphosate bi-active as a means of controlling weeds at revegetation sites where land owners are unable to undertake more labour intensive and time-consuming weed management techniques.

4.8 Vegetation Management in Highly Destabilised Reaches Subject to Bed Degradation

The revegetation approaches outlined above for the middle and upper tributary reaches where bank height is transitional or sub-critical, will generally not work well in lower reaches which are subject to substantial bed instability, locally high bed-load transport rates (ie. as a result of the re-working of stored flood plain deposits) and banks which are height constrained (dominated by mass failure). This is not to say revegetation can not play an important role in assisting to re-stabilise these reaches.

Channel sections subjected to major nickpoint incision have undergone profound changes which, as outlined in Section 4.3.3, are the cumulative response to disturbance over the last 100 years. The re-stabilisation process may take an equivalent period of time to fully implement, and as such management objectives must reflect these time scales.

The management objective for these reaches is to establish relative lateral stability, and to minimise bed-load transport. This is not going to be achieved overnight, given the extent of instability, and presumably a very limited budget. Ideally, the long term management objective for lower Missabotti Creek, North Arm and South Arm, should be to reduce channel capacity to something approaching the 1942 condition - hence reducing stream power (ie. erosive potential), increasing relative hydraulic resistance, and reducing overall channel instability. There will be a cost to the community by pursuing this objective, however, as a greater proportion of flood flow will be directed onto flood plains. The community will have to decide which is the lesser of two evils - more frequently inundated flood plains, or an ongoing unstable river channel.

No vegetation based management strategy will be effective in these reaches until the bed instability problem is addressed. Bank revegetation will almost certainly fail if it is the only approach adopted. A series of strategies addressing the bed and the banks will need to be employed to make any serious impression on the problem in these reaches.

4.8.1 Recommendations

i) A series of major bed control structures will be required - most probably appropriately designed rock weir type structures.

ii) Major toe revetment works on outer banks should commence as soon as possible, in conjunction with revegetation. These may have to be heavy engineering structures at some sites eg. steel pylon, cable and mesh structures.

iii) In most cases the only practical revegetation will be to utilise the natural regeneration of river oaks, tea trees, and callistemon. Direct seeding of these species may also be possible. Direct seeding of sedges and rushes should also be undertaken at the same time (see Section 4.9.3 for the general species types).

iv) Ongoing management of river oaks will be required - trial annual pruning to about 2 - 3 m height - or up to about bank height in later years, to encourage lower spreading habit and greater investment of the plants' resources into developing root structures. After a few years, thinning may be required as trees get bigger.

v) Once primary coloniser species have established on these revetment platforms, other species should be planted to ensure a diversity of plants capable of tolerating a range of conditions (eg. watergums and other slower growing climax species - see Section 4.9.3).

vi) Toe revetment benches should be encouraged to further build up by natural aggradation to give added protection to banks.

vii) Some upper bank battering may be appropriate on particularly high banks to enable revegetation of the bank face itself. This should only be done by excavator from the bank top to ensure no disturbance of the bank toe.

viii) In early years of toe revetment works channel width management like that undertaken on the Manning and Hunter Rivers will be necessary (see Raine & Gardiner, 1994), however, this should only be done in conjunction with bed stabilisation measures.

4.9 Willows - Godsend of Future Nightmare?

4.9.1 Lessons From other Catchments

Willows have been used successfully in a purely engineering context to help stabilise many rivers in NSW, Victoria and Tasmania. In Victoria willows have been used by river management agencies officially since the 1950s and unofficially by landowners since the early days of settlement. In recent years it has become apparent that the narrow engineering perspective upon which previous management decisions were taken, has come back to haunt the next generation of river managers. Where willows were formerly seen as the 'solution' they are now one of their major management problems in Victoria (Ed Thexton, pers. comm.). This situation also exists on rivers on the NSW South Coast and Southern Tablelands. In Victoria the problems associated with willows are now considered to far outweigh the benefits, and as such the use of willows as a river management tool has virtually ceased. Indeed, a large proportion of the Victorian river management budget is now spent trying to control willows (Rutherfurd et. al. Subm.).

In the Bega and surrounding rivers on the NSW south coast willow colonisation within the river has caused gross changes to lowland river geomorphology over the last 30 years, escalating severely over the last 3 -4 years (Brooks, 1994; Brooks & Brierley, in press). As a result, the South Coast TCM now faces spending the majority of its time and resources in dealing with the vast number of willows infesting their rivers. To make any serious impression on what is now a massive problem is probably going to require the expenditure of many thousands, if not millions, of dollars over the next decade and beyond.

There are a number of reasons why the willow problem in Victorian and southern NSW rivers has increased in recent decades, all of which could potentially occur in the Nambucca if great care is not taken. A large part of the problem is the result of the introduction in recent decades of a number of new hybrid species - particularly New Zealand hybrids, such as *Salix matsudana x alba*. Prior to the introduction of these hybrids the local willow population consisted almost exclusively of single sex weeping willows and a lesser proportion of basket willow type species such as *Salix alba*, and fairly isolated occurrences of some of the shrub willows. Under these circumstances willow self propoagation was by vegetative means only, and was fairly limited (although vegetative propagation can be a problem in some situations). The arrival of fertile hybrids of both sexes introduced a new element into the pre-existing willow community - the ability to reproduce sexually (Cremer, 1994,Cremer et. al. 1996). Sexual reproduction vastly increases the potential for feral willow colonisation in rivers, and the potential for serious geomorphic (see Brooks & Brierley, in press)and ecologic degradation of a river system.

4.9.2 Willows in Nambucca

Currently the Nambucca and its tributaries do not have a serious problem with feral willow populations and the serious geomorphic and ecologic that are associated with such outbreaks. There are a number of reasons why this is the case:

- To date the predominant willow species growing in the Nambucca catchment has been the weeping willow (*S. babylonica*)
- Weeping willows haven't tended to be the problem species in other catchments

- The NSW north coast is at the margins of the appropriate climatic growing conditions for many willow species, particularly the weeping willow
- Weeping willows in the Nambucca are subject to attack from a range of pests, further reducing their vigour in this area

Despite these factors, there is no cause for complacency.

- It is now apparent that a number of hybrid species have been introduced to the Nambucca - *S. matsudana x alba* have been introduced to both South Arm (around site S3), and on North Arm at N3.
- A seeding willow species *S. nigra* is now firmly established in the Bellinger where it is producing numerous feral seedling offspring. All it would take is one of these plants to be brought over from the Bellinger to cause a similar problem on the Nambucca.
- Seedlings of *S.matsudana x alba* have been found in South Arm (again around S3; A Raine pers. comm), indicating sexual reproduction of willows is already happening in the Nambucca, hence representing a potential source for serious outbreaks of this species, throughout the catchment. It is now known that willow seedlings can establish up to 40 km downstream from a parent tree (K. Cremer pers. comm.).

North Coast TCMs have the opportunity of pre-empting and curtailing serious willow problems in the Nambucca and tributaries, potentially saving large amounts of money that will otherwise be spent on future willow management.

4.9.3 Willows vs Natives

There is no doubt that in many situations willows will readily perform the narrow engineering role of bank stabilisers. However, in lowland river reaches subject to major bed destabilisation, even willows will not constrain the river. When weighing up the pros and cons of willows, two question must be addressed: At what cost? And, is there an alternative?

4.9.3.i Costs

The potential cost associated with future willow management can be evaluated by comparing experiences elsewhere (eg. NSW south coast, and Victoria - see above). Other costs not specifically addressed within this report, include ecological and biodiversity issues.

4.9.3.ii Alternatives

In many respects river managers on the Nambucca are fortunate because the climate and ecological conditions of the area are suitable for a diverse array of native riparian species, many of which posses appropriate growth strategies for use in river management works. Indeed, other than the use of hybrid willows (for which the future costs are likely to far outweigh the short term benefit), there is no advantage to be gained by using willows at all. Intelligent management using a suite of native species should effectively out perform the role of willows. However, greater commitment and maintenance is required to ensure the success of revegetation using native species. As outlined previously, this issue is covered in Raine (1994) and only some of the main points will be summarised here.

Fast growing primary coloniser species:

- river oaks (*Cassuarina cunninghamiana*)
- tea tree (*Leptospermum brachyandrum*)
- bottle brush (*Callistemon viminalis*)

Natural regrowth of these species or direct seeding can perform the same role as willows in stabilising point bar deposits and toe revetment platforms. All these species have root systems that extend below the water table, and when grown in dense thickets can provide substantial resistance to flow as well as gravel stabilisation. As outlined in Section 4.8.1, river oaks will perform the task best if pruned and thinned.

Sedges and Rushes:
A number of sedges and rushes will perform well in conjunction the tree and shrub species on bars and benches. Sedges and rushes are effective at trapping wash-load (see Sections 2.3.1.ii & 3.4) and hence aiding the build up of cohesive material on bench platforms. They are also effective at stabilising deposits and reducing bank surface velocity - hence reducing corrasion eg:

- *Lommandra hystrix*
- *Lommandra longifolia*
- *Scheonoplectus macronatus*
- *S. validus*

Slower growing climax species, eg:
- weeping myrtle (*Waterhousia floribunda*)
- watergum (*Tristaniopsis laurina*)
- flooded gum (*Eucalyptus grandis*)
- sand paper fig (*Ficus coronata*)
- Cheese tree (*Glochidion ferdinandi*)
- Brush cherry (*Syzygium australe*)

Again, while the latter group are slower growing, many have root systems that extent below the water table, and are dense and mat-like (similar to willows). These species can effectively colonise the in-channel zone, following the stabilisation of gravel areas by the primary colonisers, and the associated protection - both from light and high velocity flows, offered by the primary colonisers.

It must be stressed that the use of these species for revegetation work must be put in the context of both catchment scale (see Section 3.3) and bed degradation issues outlined in Section 4.3.

4.9.4 Recommendations re Willows

- All hybrid willow species should be eradicated from the catchment
- No new willow species should be introduced into the catchment. Particular care should be taken in ensuring that no black willows (*S. nigra*) find their way over from the Bellinger catchment.
- No further willow plantings should be undertaken in the catchment, other than with weeping willow if absolutely necessary.
- Recent massive willow plantings at N3 should be quickly removed and stabilisation of this site should be reassessed in light of bed-stability factors.
- Properly managed (ie. in conjunction with bed control works), river oaks and other native species can perform many of the primary colonisation functions of willows. Rather than maligning river oaks as the cause of erosion, their stabilising attributes should be utilised and the species carefully managed.

4.10 RIPARIAN BUFFER STRIPS

Many of the benefits of riparian buffer strips were reviewed by Raine (1994) and as such they will not be repeated here. Some further light can be shed on the benefits of buffer strips, however, in light of the geomorphic changes that have been imposed on the Nambucca River and its tributaries (outlined in Section 4.3). From a geomorphic perspective there are a number of benefits in having a buffer strip that extends beyond the immediate bank zone.

i) In river reaches which currently exhibit active lateral migration, it is highly unlikely that any management strategy is going to immediately halt such lateral activity. 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, a fairly minor amount of erosion result in the loss of all of the buffer zone. Hence, a wider strip will offer greater chance of a higher proportion of plants making it to maturity. This of course assumes that bed degradation issues are tackled previously or simultaneously.

ii) A vegetation strip wider than just the bank zone will have a higher resistance to flow during overbank flows. Higher flood plain resistance will further reduce in-channel velocity. The reduction of in-channel flow velocities is one of the primary long-term management objectives.
iii) 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 a greater species and hence, structural diversity. The ideal condition is the kind of structural diversity found in riparian rain forest. 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. site N3), it is hypothetically possible that if a very dense and narrow riparian zone was established with no vegetation on the rest of the flood plain, and over time the channel was substantially narrowed, that during an extreme flood the flow could adopt a preferred route down the distal margin of the flood plain, and hence cause flood plain 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 is dominated by seeding willows, and where there is no vegetation other than grass on the flood plain.

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 flood plain. These will have the effect of reducing flow velocities across the flood plain in extreme flows, and hence reducing the likelihood of flood plain stripping.

4.11 Stock Exclusion

The role of stock as agents of bank erosion is not well understood as yet in Australia. The few geomorphic studies of the role of cattle as agents of erosion come from the US (Trimble, 1995; Magilligan & McDowell, in press). These studies suggest the potential for cattle as agents of bank erosion and bed destabilisation, have probably been underestimated. That said, there are no Australian studies to draw on as to the likely role of cattle in Australian rivers.

On the Nambucca and tributaries, any assessment of cattle as direct agents of bank erosion needs to be put in the context of the underlying causes of total system instability. In this context, the relative role of cattle to date has probably been fairly minimal, in a direct sense. However, they could well have played an important role in causing Phase 1 instability outlined in Section 4.3.3. Nevertheless, we have no substantive evidence for this, as yet.

The most significant geomorphic role played by cattle at present is their secondary role in inhibiting the regrowth of vegetation. Any future management strategies incorporating revegetation strategies will have to include stock management as an integral component. Successful revegetation cannot occur while stock are continually grazing the banks. Indeed substantial natural regrowth (of both natives and exotics) would result largely by excluding stock from the riparian zone, although in many places native species may have to be re-introduced.

The issue of the role of stock on riparian vegetation and channel erosion will be examined in the final report.

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APPENDICES

Appendix 1
Vegetation Changes - Airphoto Interpretation

Introduction
Aerial photographs from 1941, 1964 and 1991 were analysed throughout the catchment to assess gross changes in the extent of riparian vegetation, as well as any associated changes to river geomorphology. This analysis was limited to a qualitative assessment of both vegetation extent and geomorphology. This sort of analysis is however, invaluable for assessing the associations between channel behaviour and vegetation over the 55 years or so covered by the airphoto record. The comments included in this appendix are initial qualitative impressions only and require further detailed air-photo interpretation at specific sites, as well as substantial investigation on the ground to confirm the general trends described below. Detailed air-photograph mapping is presented in working paper number 5, from which quantitative comparisons of channel activity will be made for selected sites throughout the catchment.

Evidence for channel change was interpreted by drawing on the following evidence:

- Channel width - changes fairly obvious from the photos
- Sinuosity - cut-offs readily detectable
- Bed level lowering - this can be discerned using various lines of evidence:
    - i) visually using a stereoscope
    - ii) gully incision through small tributaries flowing across the flood plain is commonly associated with bed lowering of the trunk stream (ie. small scale nickpoint retreat up these tributaries in response to base level lowering). These are readily discernible from the later airphotographs.
    - iii) In addition, channel widening generally follows the upstream migration of a nickpoint. If substantial channel widening is evident, starting at the bottom of a tributary and proceeding upstream, there is a good chance it is associated with the upstream migration of a nickpoint

- Pool in-filling - readily discernible from airphotos
- Bed-form homogenisation - ie. the removal (lowering) of riffles and in-filling of pools

Vegetation species level differentiation was rarely possibly, other than the identification of large river oaks or colonies of juvenile river oaks. Guesses can be made at certain locations as to the likely composition of dominant species, based on contemporary species composition.

Supplementary evidence to support observations made in this analysis is presented in part b of this appendix, at representative sites throughout most of the tributaries. These plates show comparisons between the oldest and most recent airphotos available. Not all tributaries could be represented here due to the limited coverage of the 1942 photo series. It is acknowledged that the quality of these reproductions is poor - they have been included simply to provide supporting evidence for the claims made from detailed stereoscope interpretation. It is recommended that proper photographic enlargements be made of these sites as an education tool for the local community.

Disclaimer re. Inferred Pre-European channel condition:

The inferences made regarding the possible condition of the pre-European channel are a first approximation only, based on:

- historic accounts
- the 1942 airphotos
- what is known about the likely composition of the pre-European vegetation community
- the authors experience from elsewhere
- theoretical knowledge regarding vegetation interactions in rivers

Missabotti Creek:

Upper Missabotti (around M1) See Plate 1

Inferred Pre-European channel:

Channel significantly narrower than in 1942. Banks possibly lower than 1942 condition although not absolute. Banks below critical height - hence corrasion dominated. Sinuosity probably somewhat higher. Woody debris loading would have been high and fairly evenly dispersed (ie. logs remaining in situ where they fell, with many large logs traversing the entire channel. Some jams may have occurred - smaller debris backed up a against large key-member log. The logs would have exerted significant control on bed level. Bed level variation would have been much more extreme than was the case in 1942 and subsequently - deeper holes and more pronounced riffles. Channel avulsion, possibly initiated by log jams may have dominated over gradual lateral migration in the less confined reaches. Due to the substantially higher bank strength values associated with dense rain forest vegetation, rates of channel migration probably at least an order of magnitude lower than today. Gravel throughput would have been minimal due to: bed armouring (phylite gravels still dominate here), and riffles stabilised by woody debris and possibly macrophytes and aquatic weeds. Only in extreme droughts would this channel have gone dry.

1942: Virtually no vegetation along channel at all (other than grasses). Hillslopes cleared to much greater extent than is apparent today. Channel at this stage seems very broad and relatively stable, however indications are that it has expanded in the not too distant past. Some pools are evident associated with bedrock constricted bends. Woody debris not evident.

1964: Extent of riparian vegetation little changed from the situation in 1942 (ie. virtually none - few scattered large oaks). Channel is a broad unstable gravel bed channel with extensive gravel point bars and cut banks. Many pools now in-filled.

1991: Riparian vegetation (most probably dominated by River Oaks) has increased substantially since 1964 in selected reaches. However, significant lengths of channel still without vegetation. Channel condition similar to that in 1964 although probably less active (ie. slightly more stable). Inset benches are evident, possibly indicating some channel incision. 1997 field observation suggests this probably is the case, given the presence of a number of nickpoints in this vicinity. Channel sinuosity appears slightly higher in 1991 than 64 or 42. Hillslopes show significant regeneration of forest since 1964 and 42 - ie. right down to the bottom of steep slopes in many cases (as is the case today).

Field obs. 1997: Following recent spate of floods upper Missabotti has become active once again, with a series of nickpoints re-activating and migrating upstream.

Middle Missabotti Creek (around site M2) see plate 2

Inferred Pre-European channel:

Channel significantly narrower than in 1942, and probably significantly more sinuous in sections where the river has room to move. Banks possibly lower than 1942 condition although again this is not absolute. Banks still below critical height - hence still corrasion dominated. Woody debris loading would have been high and still fairly regularly spaced, log length would still have been substantially larger than channel width. Possibly more jams may have occurred - still of the type dominate by smaller debris backed up a against large key-member log. The logs would have exerted significant control on bed level. Bed level variation, again would have been much more extreme than was the case in 1942 and subsequently - ie. deeper holes and more pronounced riffles. Meander cutoffs probably dominated here, in areas where floodplain is broader, although avulsion still possible. Gravel throughput would have been higher here than the upstream site, due to both increased discharge and less bed armouring here, however woody debris stabilisation and a relatively stable bed level would mean total bedload transport would have been substantially less than today. Same comments apply re- perennial nature of flow.

1942: Virtually no riparian vegetation at all on banks or in the channel itself - channel completely denuded. Channel in the reach above the bridge is completely straight and showing signs of erosion and significant gravel transport at this time - ie. eroding banks along both sides of the channel. Little evidence of pools and riffles, except further upstream where there are scour holes associated with bedrock bends. Appears to be a large gravel splay just downstream of the bridge. Kennaicle Ck unincised at this time, ie. major channel incision not evident at this time. Woody debris not evident.

1962: Some vegetation beginning to establish within the channel in certain reaches (presume river oaks). Channel highly unstable with many vertical banks on outside bends - often where there is no associated vegetation colonisation on point bars. Few trees evident on the tops of eroding banks. Reach upstream of bridge appears to have aggraded at this time - possibly indicating temporary accumulation zone for gravel released upstream in previous decades. Kennaicle Ck apparently beginning to incise at this time although scale of photographs makes it difficult to be conclusive about this.

1991: Substantial increase in the extent of riparian vegetation by this time, particularly within the channel - both on the inside and outside of bends. Channel above the bridge has a substantially higher sinuosity and would appear to be more stable here than either the 64 or 42 photos. Kennaicle Ck has incised significantly, with severe headcuts evident moving up this tributary - apparently having been triggered by base level lowering on the Missabotti. Hence it appears nickpoints may have been through the reach above the bridge, releasing sediment from upstream and temporarily storing it in this section. As with upper Missabotti, significant regeneration of hillslope vegetation between 42 and 91 (see plate 2).

Field obs. 1997: Since early 1995, this reach (ie. the reasonably stable section above the bridge) has been reactivated once again. A nickpoint (or series of nickpoints) have migrated upstream through this reach since early 1995, causing substantial reactivation of stored gravels. Significant tree fall was associated with the bed lowering and subsequent channel widening.

Lower Missabotti Creek (around site M4) see pate 3

Inferred Pre-European channel:

Same comments apply as for middle Missabotti + : Bedload transport marginally higher than middle Missabotti, due to a higher proportion of quartz gravel comprising the bedload here. Some woody debris may be getting swept around by flows to buffer bank toes. Localised channel expansion, and contraction possibly associated with log jams may be a more important process here, although meander cutoffs and realignments are evident in the less confined reaches. Bank height may be approaching critical height here (needs field confirmation), particularly associated with localised scour at log jams where bank vegetation is removed. In general, however, banks will have been well graded and fully colonised by a range of species, and hence not subject to mass failure. As a result of narrower and much more pronounced and well vegetated point bar/bench deposits, channel capacity and hence stream power considerably less than at present.

1942: Channel zone densely vegetated in parts - particularly in reach just upstream of site M4. Other sections further upstream less vegetated. Channel seems pretty stable at this time, although substantial in-channel gravel deposits as point bars are evident indicating there may have been significant gravel throughput in the not too distant past. These deposits are grassed over, and in some cases vegetated with shrubs - No apparent pressure on outside banks as a result. Some pools evident both on bends and in straight reaches. Large palaeo-channel evident in floodplain indicating former lateral activity of channel.

1964: Channel severely eroding at this time - significantly wider and apparently deeper. Substantially less vegetation in the channel *cf* 1942, particularly in reach just upstream of severe bank erosion on the right bank at M4. Channel slightly straighter, and dominated by extensive gravel deposits as point bars and lateral bars.

1991: In some reaches there has been a significant build up of vegetation both within the channel and on the banks (presumably river oaks on the banks and in the channel + tea tree in the channel). In other reaches there has been substantial vegetation clearance since 64 - Overall, the extent of vegetation on lower Missabotti is similar to that in 1964 - however it is located in different positions. Significant build up on bar up stream of site M4, ie. at site with severe lateral migration. Overall channel appears narrower than in 64, except at extraction sites. Extensive gravel extraction of point bar/floodplains evident.

Field obs. 1997: At site M4 there has been a continued build up of vegetation within the channel - ie. on the point bar opposite the severely eroding bank. This local build up of vegetation within the channel has deflected flow to the outside bank, causing continued erosion of this site.

North Arm Nambucca River

Upper North Arm (around sites N1/N2)

Inferred Pre-European channel:

Same comments apply as for upper Missabotti + overwidening up to 1942 probably even more pronounced than upper Missabotti, thus in relative terms pre-European channel even narrower *cf* 1942.

1942: Only minimal scattered riparian vegetation evident - predominantly river oaks. Pools evident at bedrock bends. This part of upper North arm shows evidence for channel expansion in the recent past (can't discern whether post-European or not). Channel is somewhat overwidened with the low flow thalweg meandering within the channel. Natural revegetation by shrubs evident on the eroded banks.

1964: Still only minimal riparian vegetation at this time - similar extent to that in 42, or possibly less. Channel condition doesn't seem to have changed that much since 42 (although photo scale poor). Pools still evident, channel alignment same. No conspicuous erosion of alluvial flats.

1991: Hillslopes show substantial forest regeneration *cf* 64. Riparian vegetation extent has increased somewhat, although only at selected sites, where there are more river oaks. Channel instability has increased since 64 & 42 although not markedly. Some minor lateral migration evident, and possibly some incision as a series of inset benches are evident in places. No apparent correlation between sites of lateral expansion and river oak build up (ie. some areas where erosion occurs have no vegetation at all, others have some vegetation).

Field obs. 1997: Continuation of the trend between 64 and 91- ie. continued lateral expansion in areas of discontinuous floodplain. Seems to have been an acceleration of activity over the last 6 years.

Middle North Arm (around N3 @ Argents Hill) see plate 6

Inferred Pre-European channel:

Same comments apply as for middle Missabotti + similar to upper North Arm, over-widening up to 1942 probably even more pronounced than upper Missabotti. The channel in this reach is less confined than middle Missabotti, and is just below a relatively confined sediment transfer zone. As a result this site appears to have been fairly laterally active in the past, although again, the substantially higher bank strength values associated with dense rain forest vegetation would mean channel migration rates were probably at least an order of magnitude lower than today. Large meander cutoffs and possibly channel avulsion were likely to have dominated in this reach.

1942: Fairly sparse riparian vegetation, although substantially more than at present. Almost entirely river oaks, scattered large ones in right bank floodplain, and a line of large oaks around the base of the hillslope opposite N3. Low flow sinuous channel thread flanked by a low inset floodplain meanders between a higher primary floodplain (ie. in addition to the terrace). This low inset floodplain forms an extremely wide channel, indicating substantial instability within this reach in the past. Pools evident on outside of bend (ie. subsequently cutoff). No significant pool upstream of current rock weir site, instead there is a large partially vegetated gravel bar in this section.

1964: Substantial channel instability evident at this time. Channel now wide with eroding outer banks. Less vegetation in channel than 42, while vegetation on the right bank floodplain has perhaps increased. Area where vegetation has increased is not the principle erosional area. Upstream of N3 there are extensive sections of river which area actively migrating laterally. There is very little vegetation in these reaches at this time.

1991: Vegetation upstream of N3 has increased markedly since 64. Virtually all vegetation on the right bank floodplain at N3 has gone since 64, apparently the whole lower inset floodplain has been reworked since 64. A substantial cutoff has also occurred in this period. No pools evident - channel is a broad gravel sheet.

Field obs. 1997: Considerable lateral expansion has continued over the last 6 years as has extensive gravel extraction and river engineering works (all of which have failed - with the exception of a rock weir). These works included significant plantings of willow and native plants.

Lower North Arm (around N4 - N5) see plates 4 & 5

Inferred Pre-European channel:
Same comments apply as for lower Missabotti + less evidence here for meander cutoffs as a significant mechanism in channel realignment.

1942: Channel lined with discontinuous stands of large river oaks, many are on bedrock bends however. Significant extent of other shrubby vegetation (possibly willows?) on banks. Apparently older on outside banks and young regeneration on point bars and inside bends. Macrophytes evident in low flow water course and in some pools. Substantial point bars in the channel at this time, in many places well vegetated. Outer banks opposite these bars appear stable. Channel capacity is considerably less than at present due to the extensive deposits contained within these point bars. Few vertical banks evident. Numerous pools evident both on bends and along straight reaches.

1964: Significant channel incision and widening evident at this time. Riparian vegetation appears somewhat less than in 42. Much of the reduction is associated with the erosion of point bars and the vegetation associated with these. Small tributaries running across floodplain have headcuts moving up them, indicating significant bed level lowering between 42 and 64.

1991: Substantially more riparian vegetation, presume largely river oaks, along the lower north arm at this time. Little apparent change to overall channel dimmensions *cf* 64. Significant gravel extraction evident on point bars and floodplains along this reach. Little evidence for vegetation colonisation within the channel - suspect this may have something to do with extraction disturbance. Substantial regeneration of hillslope forest evident between 42 and 91 (see plates 4 & 5).

Field obs. 1997: Continued build up of riparian vegetation in this reach, including some in channel colonisation. Unclear whether bed degradation is continuing to the present day along the lower reaches of North Arm. More likely that aggradation is now occurring, but can't confirm this.

Buckra Bendinni Creek:

Mid Buckra Bendinni (around site B2) see plate 7

Inferred Pre-European channel:
A very low capacity channel between deep scour pools at bedrock bends. Bedload throughput almost negligible. Rainforest vegetation probably encroached right into the channel in the

sections of channel between the scour pools, making the channel extremely resilient in these reaches. Woody debris would have comprised a large proportion of channel cross sectional area, almost entirely of windthrown origin (see comments in section? of main report), but outside of the deep pools may not have lasted extreme periods of time due to dessication. Lateral channel movement very limited and rare - probably only associated with in frequent extreme events (eg. >> 1:100 year events), in which case it was likely to have been channel avulsion or extensive channel expansion in the riffle zones. Bed level variation probably not that dissimilar to the 1942 situation. Banks corrasion dominated. Flow largely perennial, although it is likely that flow may have been reduced to just a trickle between the large pools fairly frequently.

1942: Channel much narrower than at present however includes substantially build up in riffle zones making the channel zone indistinct between pools. Fairly large pools evident at bedrock bends, with macrophytes. Channel much wider at the pools. Riparian vegetation minimal at this time. Some scattered river oaks and a few small shrubs along both banks - predominantly grass however. The channel appears relatively stable at this time, almost like a form of "chain of ponds" style stream.

1964: Little change in the extent of vegetation between 42 and 64. Neither has overall channel position has changed very much. There has however, been some incision of the riffle zones linking the large pools. A few vertical eroding banks are evident at this time.

1991: Little change in the extent of riparian vegetation between 42 and 91 is evident. Channel instability is substantial at this time. Riffle zones between the pools have deeply incised and substantial channel expansion has occurred, releasing significant volumes of sediment. The large pools described above have largely in-filled.

Field obs. 1997: The trend identified between 64 and 91 has continued to the present day. It is not possible to judge whether there has been an acceleration of the channel erosion over the last 6 years. There appears to have been little increase in the extent of vegetation.

Lower Buckra Bendinni (around site B3) see plate 8.

Inferred Pre-European channel:

Channel condition here was remarkably different to the upstream reaches. Valley is much less confined and as such there is a broad expanse of floodplain through which a well defined meandering channel flows. In the reach upstream of B3, this situation is not that dissimilar to the 1942 condition or indeed the present condition (ie. upstream of the incised lower reaches of Buckra Bendinni Ck.). Numerous old cutoff channels are evident in the floodplain, suggesting the channel here was meandering back and forth across the floodplain albeit at a fairly slow rate. Bank height was sub-critical and hence corrasion dominated. Undercut banks would have been common, although being held up for substantial periods of time by the dense root mats of the dense rain forest. Woody debris loadings in the channel would have been extreme, possibly in excess of 50% in some places. A high proportion of this debris would have been sub-canopy rainforest species (ie. of the type in the second category outlined in section ?? main report). Channel width was well below the canopy height, meaning most woody debris remained lodged in the channel where it fell. Only minor log jams formed, possibly aiding bend migration at specific sites. Bed level variation would have been greater than at present due to the greater role of woody debris, and the lower bedload throughput. Flow would have been perennial, very rarely ceasing to flow.

1942: Narrow but fairly well vegetated riparian strip (ie. primarily on banks) along the lower Buckra Bendinni at this time. Channel and floodplain characeter is fundmentally different around B3 and down to the South Arm confluence, *cf* site B2. Broad floodplain with narrow sinuous channel. Many recent and former cutoffs evident. This style of behaviour would appear to be characteristic of the longer term behaviour in this reach. At site B3, channel alignment and character not significantly different to present. Pool evident on RH bend + more vegetation in channel than at present upstream of bend. Little sign of gross channel instability along lower B.B.ck at this time - other than a few small cutoffs.

1964: Riparian vegetation not that different to the 1942 situation. Little evidence of gross channel instability at this time between B3 and South Arm confluence - other than a couple of fresh gravel point bar deposits, indicating there may have been some additional bedload beginning to work its way down through the system from the in-channel erosion outlined above (@B2).

1991: At selected sites vegetation extent has increased cf 1942 - particular in the reach just above the Sth Arm confl. However, in other sections vegetation is approximately similar to or even lightly less than that in 1942 (eg.U/S of B3). At this time significant bed lowering is evident along the entire lower section of Buckra Bendinni Ck (& lower South Arm). Incision of small floodplain tributaries is evident to support this observation. Channel expansion is also occurring in the lowest part of this reach. Overall planform has not changed significantly at this time.

Field obs. 1997: The extent of destabilised channel evident in the 1991 photos doesn't seem to have changed significantly in the last 6 years (at site B3 anyway - which represents the approximate upstream limit of bed incision in 91). Reports are that channel expansion has continued.

■ **South Arm**

Upper South Arm (around sites S1/S2 - Jaspers Ck confluence) see plate 9

Inferred Pre-European channel:

Comments as for upper Missabotti and Upper North Arm pretty much apply here. Differences here are that the bedload throughput will probably have been even lower due to the gravel largely being of phylite origin and hence well armoured. The channel is also more bedrock confined, hence there was little opportunity for channel migration.

1942: Relatively little riparian vegetation evident at this time + hillslopes extensively cleared. Channel fairly stable laterally, although largely bedrock controlled in this section. Some recent channel expansion evident with fresh gravel deposits on some point bars evident. Pools evident but apparently not that deep as they seem to contain extensive macrophyte growth. Macrophytes also grow in the low flow water course.

1964: Little change from 42 situation in terms of vegetation extent - except that macrophytes have been stripped from the in-chanel zone. Some evidence for recent gravel bedload transport, with fresh gravel point bars evident. Gross instability not evident, however.

1991: More riparian vegetation than 64, particularly at selected sites (ie. not uniformly ditributed along the stream), predominantly river oaks. Further down the reach (ie. below S2.) lateral channel migration is evident in alluvial flats, at sites both with and without vegetation on the inside bends. Upstream of site S2 channel is not much wider than in 1942 - it is just more homogeneous (ie. riffles reduced and pools infilled) - no sign of macrophytes in low flow water course. As with many other locations around the valley, substantial hillslope forest regeneration is evident *cf* 64 and 42.

Mid South Arm (around sites S3- Sth Arm/McHughs Ck Confl.) see plate 10

Inferred Pre-European channel:

Comments as for middle North Arm largely apply here. Again the nature of the gravel differs here in comparison to North Arm, in that it is also phylite dominated, and hence has better armouring potential. Overall channel instability here was probably less than middle North Arm. Channel avulsion and expansion may have been significant here in addition to some meander cutoffs. Bank height was still sub-critical, and bed level was relatively stable due to the bed armouring and woody debris. Dense riparian vegetation here would have significantly reduced rates of lateral channel activity *cf* today.

1942: Riparian vegetation consists of scattered large River Oaks and macrophytes growing extensively in the low flow water course. Channel at confluence zone is broad and fairly indistinct. Eroding banks not obvious at this time, however, there are numerous "old" cut banks on the floodplain indicating there has been substantial lateral activity at this site in the past. Channel is significantly straighter at this time than at the present. Pools not really that obvious, although there are slightly deeper sections of channel with extensive macrophyte growth in them.

1964: Channel is somewhat incised and more laterally active than 1942. Right at the confluence zone has more vegetation than previously (presumably river oaks), while the majority of the floodplain has little more vegetation than in 42. Macrophytes gone from in-channel zone. No firm correlation between lateral migration areas and vegetation build up.

1991: Substantially less vegetation in this reach than in 64 and 42. Floodplain upstream of S3 almost completely denuded of vegetation. Lateral migration of channel has progressed significantly since 64 - channel has significantly higher sinuosity at this time *cf* 64 and 42. Downstream of S3 channel incision and expansion is evident. Tributary incision evident that was not in 1942. Extensive gravel extraction evident at this time, including floodplain extraction and an apparent meander cutoff.

Field obs. 1997: At confluence site lateral migration of channel has progressed significantly, despite (or because of) recent channel rehabilitation works. Log sills placed by the task force in 1995/6 appear to have diverted the flow into eroding banks, increasing lateral migration rates. Some recent toe revegetation works appear to have had some limited success in halting outside bend migration. NZ hybrid willows used as bank stabilisers at this site.

Lower South Arm (around sites S4 + below Buckra Bendinni Ck confluence) see plate 11

Inferred Pre-European channel:

The condition of the channel on lower South Arm was (and still is) dramatically different to the upstream conditions. Whilst the middle reaches of South Arm were more akin to the situation on North Arm, the lower reaches are more akin to the lower reaches of Buckra Bendinni. That is a highly meandering system, subject to cutoffs. The primary difference *cf* Buckra Bendinni is the nature of the bedload - ie. phyllite dominated gravels. As a result the channel was less active than lower Buckra Bendinni. Otherwise the same comments for lower Buckra Bendinni apply.

1942: Fairly well vegetated riparian zone evident at this time, right down to Bowraville. Much of this vegetation appears shrubby. Extensive pools evident a km or so above Bowraville as are large riffles. Adjacent to Bowraville the channel is quite unstable, where there are 3 quite large cutoffs. (North Arm not unstable at this time). Some of the upstream riffles showing signs of instability - ie.exposed gravel, however no signs yet of substantial nickpoint migration above the lowest couple of km of South Arm. Bank erosion generally not evident at this time, apart from the bottom km of Sth Arm. At least 7 cutoffs can be seen between the Buckra Bendinni confluence and Bowraville, either in the process of forming or having recently formed - ie. sinuosity has been reduced quite considerably in this reach in the recent past - substantially increasing channel slope and energy gradient.

1961: Riparian vegetation has increased along the lowest reaches of South Arm by this time but so has channel incision. Incised tributaries all along lower South Arm. South Arm incision extends upstream as far as Buckra Bendinni at this time.

1991: Lower South Arm incision has now progressed up stream of the B.B. Ck confluence, but up Buckra Bendinni - not South Arm. Vegetation has increased on South Arm to some extent *cf* 1964, both above and below the confluence with Buckra Bendinni. Channel condition above BB Ck confluence is unchanged from the 1964 situation, whereas downstream of the confluence there has been substantial channel expansion - ie. the channel destabilisation is a function of time elapsed since the passing of the nickpoint (or points)as they migrated upstream - not the degree of vegetation.

■ Taylors Arm

Upper Taylors Arm (above site T3) see plate 12

Inferred Pre-European channel:
Same comments apply as for upper South Arm

1942: Riparian vegetation fairly minimal at this time - scattered large river oaks, and shrubs along formerly cut banks. Pools are evident at bedrock bends, however indications are that there has been channel expansion in this reach in the not too distant past. Large point bars are obvious, now partially vegetated with scattered low shrubs (species unknown). Despite evidence for former channel activity, sediment production from this area is low at this time. No channel incision evident.

1964: Less riparian vegetation than in 1942, and channel more active. Whilst channel is largely bedrock controlled in this reach, laterally migration is evident in discontinuous floodplain sections. Pools are still visible at bedrock bends although apparently somewhat in-filled. No evidence for major channel incision at this time.

1991: Significant increase in the extent of riparian vegetation - primarily river oaks at selected sites (ie. not a continuous vege build up). Channel wide and shallow, and possibly somewhat deeper, however, shallow pools still visible at similar locations to those in the 42 photos. Significant lateral migration into alluvial flats downstream of Thumb Ck. No direct correlation between vegetation build up and sites of lateral migration.

Mid Taylors Arm (around site T5- T7) see plate 13

Inferred Pre-European channel:
Channel significantly narrower than at present, and more sinuous in less confined reaches. Mean bank height probably only slightly less than today and still largely sub-critical - although in terms of geotechnical bank conditions, this reach may have been transitional - ie. mass failure may have occurred locally where bank vegetation had been removed at log jams, for example. Overall, the banks through these reaches would have been well graded and vegetated by a diverse range of riparian rainforest species. Woody debris, may still have crossed the entire channel, however, there would have been an increasing tendency for logs to be swept around parallel to flow. Debris probably would have comprised less than 20% of channel cross section, and would have consisted of both windthrown and fluvially dislodged logs. Bed level control associated with woody debris would still have been significant. As with all other sites, bed level variation would have been much more extreme than is presently evident.

1942: Reasonable amount of vegetation in this section of river, although somewhat patchy. Less in alluvial sections than in bedrock sections. Vegetation dominated by shrub species, presumably such as willows, Callistemon, Leptospermum, sandpaper fig etc.

1964: A number of cutoffs evident at this time between sites T3 - T6. Substantial channel widening also evident. May be some local bed incision in this reach. But no wholesale incision migrating upstream through this reach (downstream bedrock bars prevent such nickpoint migration). Any nickpoints active in this area are of local origin.

1991: More vegetation than 64. Channel wide and laterally active, although not that much more than in 1964. Evidence for some channel incision between T3 and T6 (ie. incised tributaries), but nothing like that in the streams in the northern part of the catchment. Most lateral migration focused in reach between T3 and T5. Below about T7 channel becomes much narrower, and stable. Large pools still visible in this section of river.

Lower Taylors Arm (around site T9 & T10) see plate 14

Inferred Pre-European channel:

The channel along lower Taylors Arm is largely bedrock controlled - on the bed and laterally. Riparian vegetation under these condition has little influence on overall channel morphology. By and large, channel morphology would have been similar to the present condition, although due to light supression of the dense rainforest canopy on both banks, there may well have been less in-channel vegetation than at present. Obviously no exotics. Woody debris may have formed substantial discontinuous jams here from time to time, which may have led to localised bank scour, particularly if they catastrophically burst. Many of the larger pools would have been deeper, due to the lower bed loads prevailing at this time (ie. those that have been in-filled in recent times).

1942: Fairly dense riparian vegetation - particularly dominated by shrub species in the channel - presumably - Tea tree, Callistemon, willows etc. Large pools evident. Channel appears stable, although considerable bedrock control through the lower reaches of Taylors Arm prevents much lateral activity. No appreciable gravel accumulations in pools.

1964: Channel condition fairly similar at this time with the exception of one large point bar deposit 4 - 5 km downstream of Taylors Arm. This and a couple of point bars around T7 are the only real indication of an increase in sediment supply associated with the channel expansion between T3 - T6. Presumably much of this sediment yet to work its way through the system.

1991: Channel at this time very similar to the 1964 condition. Still little gross evidence for substantial amounts of gravel working there way through the lower reaches of Taylors Arm. Large bedrock pools still evident around T9 and T10. Vegetation extent similar to 1964, although structurally it will undoubtedly have changed over this time.

■ Warrell Creek

Eungai Creek (around site W2)

Inferred Pre-European channel:

In gross geomorphic terms this channel would have been similar to the present condition. (the same cannot be said in ecological terms). Channel widths would have been similar. Bed level variation may have been more pronounced than at present (ie. there is some evidence that bedload has marginally increased, in filling pools and possibly lowering riffles . Woody debris loading would have been higher. As there has been sporadic removal by landowners + new recruitment has been significantly lower since floodplain clearance, particularly windthrown debris. Lateral instability negligible in this channel.

1942: unavailable

1964: Densely vegetated riparian zone presumably dominated by water gums (*Tristaniopsis laurina*) at this time (as is the case at present). Channel effectively stable. Channel appears little different to the present day.

1991: unavailable

Field obs. 1997: Stable, well vegetated riparian zone, dominated by water gums. Significant weed invasion - primarily privet. No evidence of channel instability. Bedload minimal compared with other streams throughout the valley - although some landowners suggest there has been an increase in the volume of bedload. At the time we inspected sites around the valley (during a minor fresh), Eungai Ck. had the highest unit suspended load of all the tributaries.

Lower Worrell Creek (around site W3)

Inferred Pre-European channel:
Same comments apply as for Eungai Creek

1942: unavailable

1964: Well vegetated and largely stable channel system along the entire lower reaches of Worrell Ck. Vegetation presumably dominated by water gum at this time.

1991: Channel appears little different to the 1964 situation in gross terms.

Field obs. 1997: Again, as with W2, little apparent change in overall channel condition or extent of vegetation over recent years/decades. Principle problem in this channel is weed invasion - primarily privet. Unable to tell whether privet was a substantial component of the vegetation community in the previous time-frames.

■ Deep Creek

Mid Deep Creek (downstream of site D2)

Inferred Pre-European channel:
Same comments apply as for Eungai Creek + some lateral instability may have occurred - principally channel migration and meander cutoffs, albeit occurring at a very slow rate. Consequently, woody debris loadings may have been higher than the almost completely stableEungai and Warrell Creeks.

1942: unavailable

1964: Narrow riparian zone densely vegetated at this time. Channel appears stable - ie. very similar to the present condition.

1991: unavailable

Field obs. 1997: Channel condition little changed from the 1964 situation. Vegetation dominated by water gums. Channel stable.

Lower Deep Creek (around D3)

Inferred Pre-European channel:
Same comments apply as for Mid Deep Creek

1942: Unavailable

1964: Substantially more vegetation on both banks downstream of the road crossing at this time and channel appears stable. Channel upstream of the crossing is stable at this time as well.

1991: Unavailable

Field obs. 1997: Significant instability below crossing at present, with left bank severely eroding. No vegetation on this bank now. Can't say without further information on this site what the sequence of events were here that lead to this localised instability. Channel instability only seems to extend as far as the first bend upstream of the crossing. Recent stabilisation works have been undertaken on this bend, using jacks and a range of native trees and shrubs. Too early to measure their success yet.

Appendix 2 - Airphoto Comparisons 1942, 1991

Plate 1: Upper Missabotti Ck. around site M1 - 1942 LHS; 1991 RHS

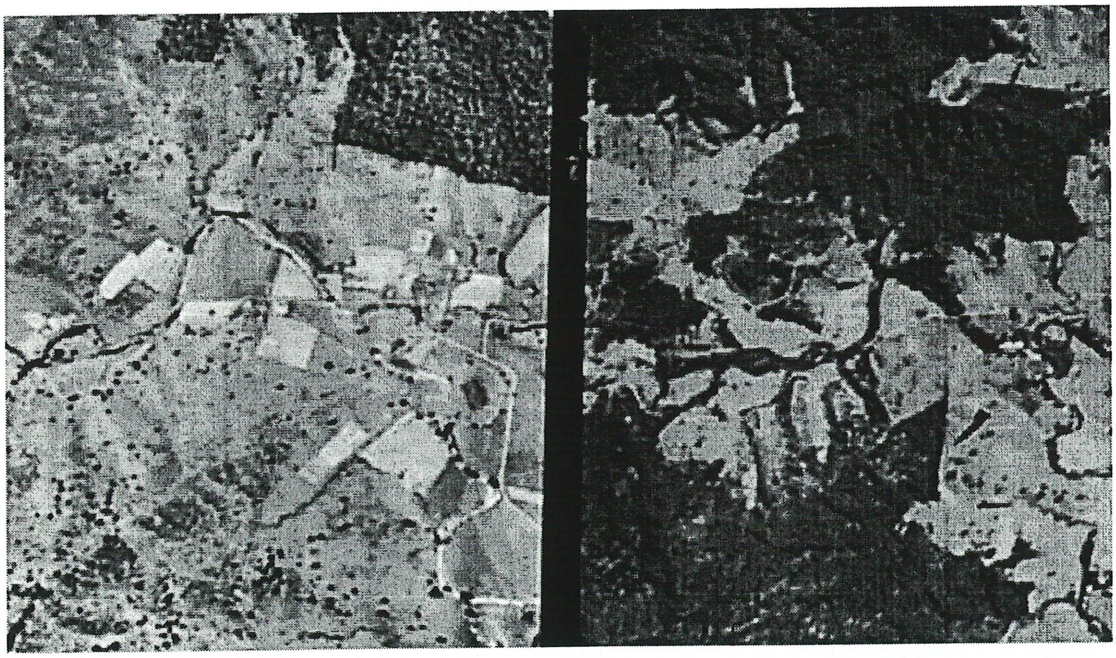

Plate 2: Middle Missabotti Ck. around site M2 - 1942 LHS; 1991 RHS

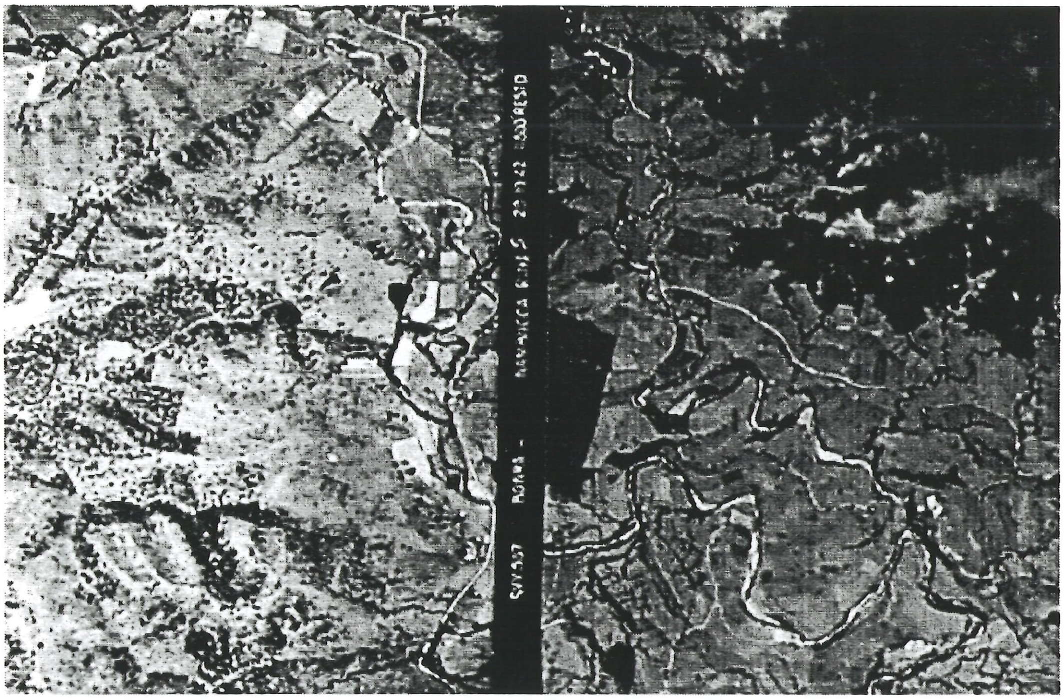

Plate 3: Missabotti Ck. around site M3 & M4 - 1942 LHS; 1991 RHS

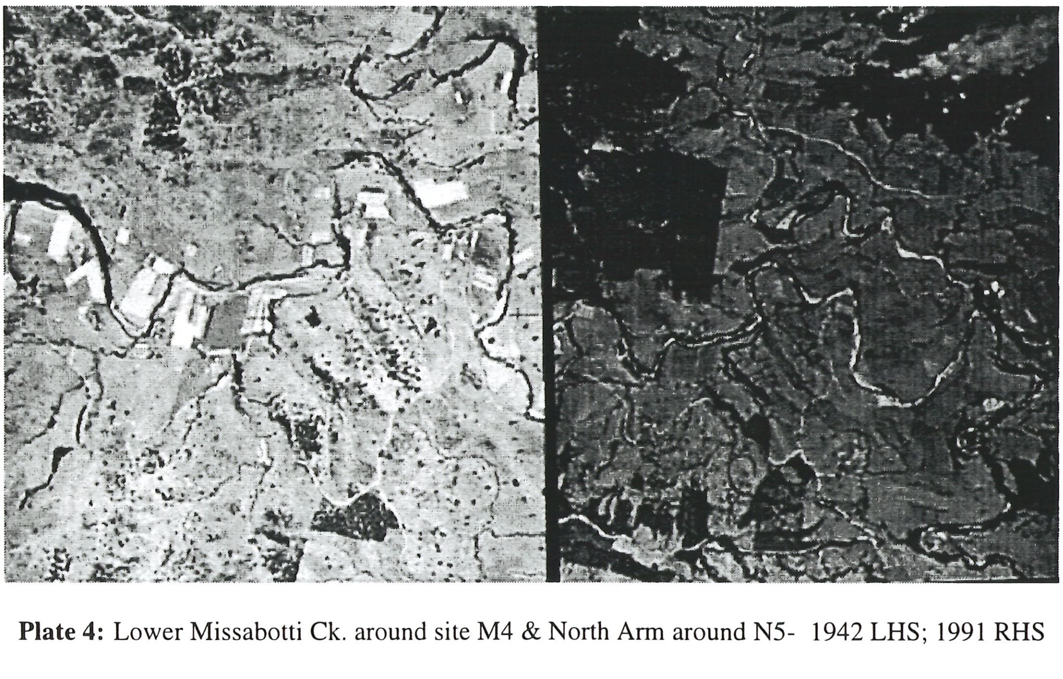

Plate 4: Lower Missabotti Ck. around site M4 & North Arm around N5- 1942 LHS; 1991 RHS

Plate 5: Middle North Arm around site N4 - 1942 LHS; 1991 RHS

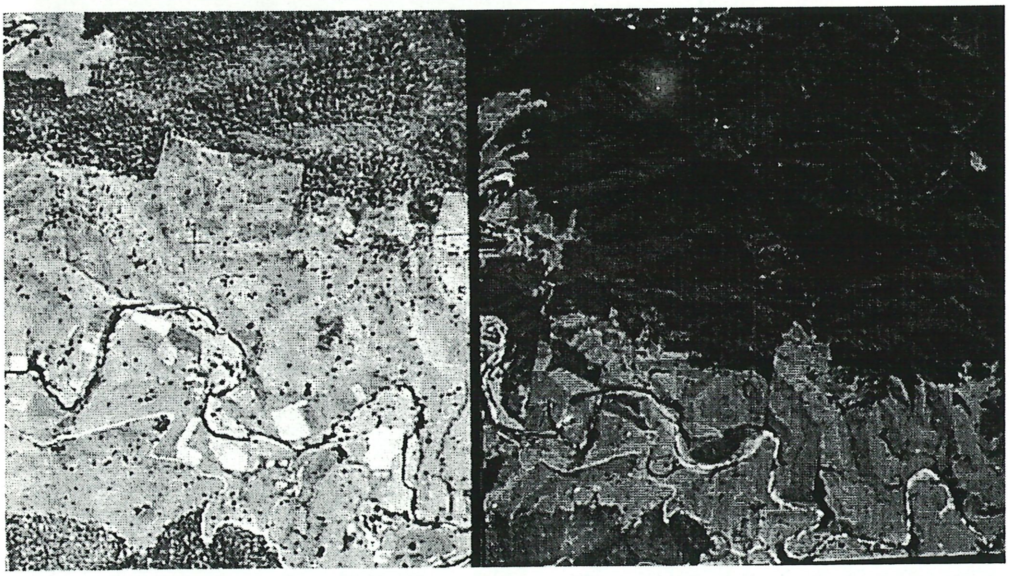

Plate 6: North Arm at Argents Hill, site N3 - 1942 LHS; 1991 RHS

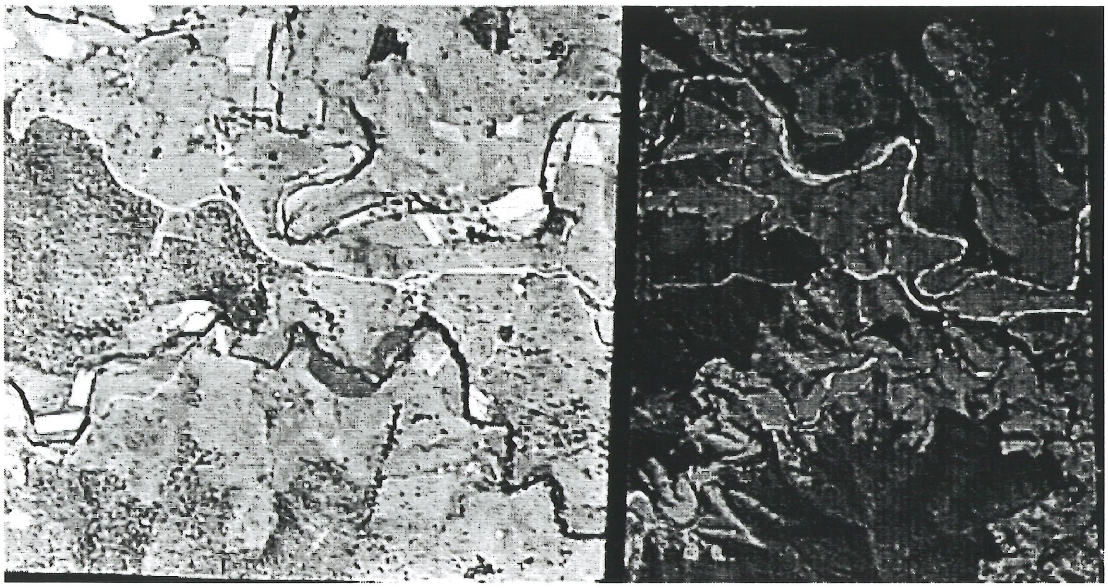

Plate 7: Buckra Bendinni Ck. around site B2 - 1942 LHS; 1991 RHS

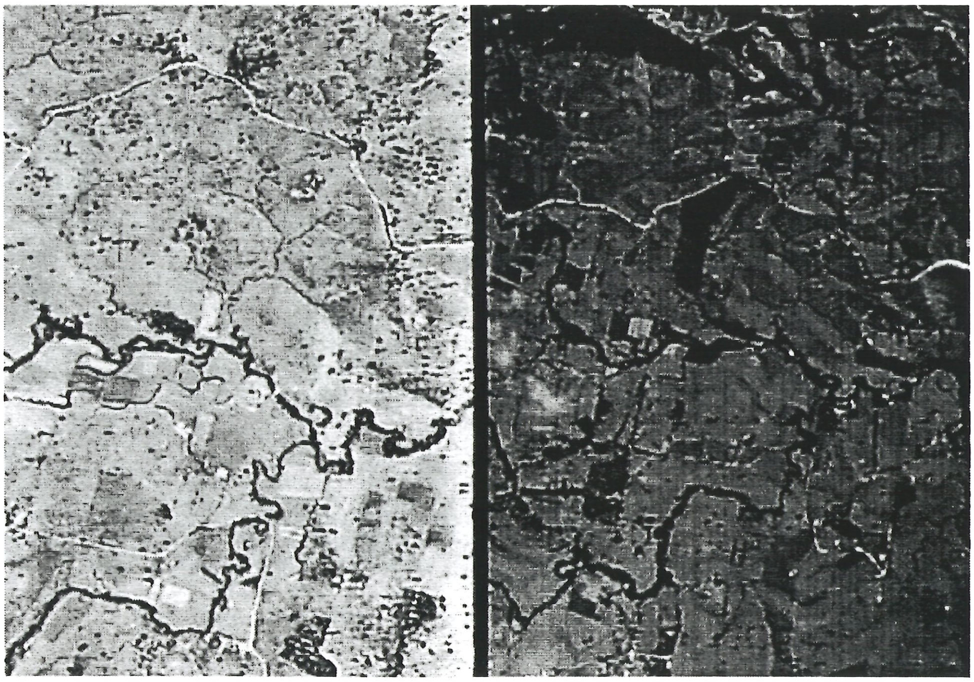

Plate 8: Buckra Bendinni Ck. and South Arm Confluence - 1942 LHS; 1991 RHS

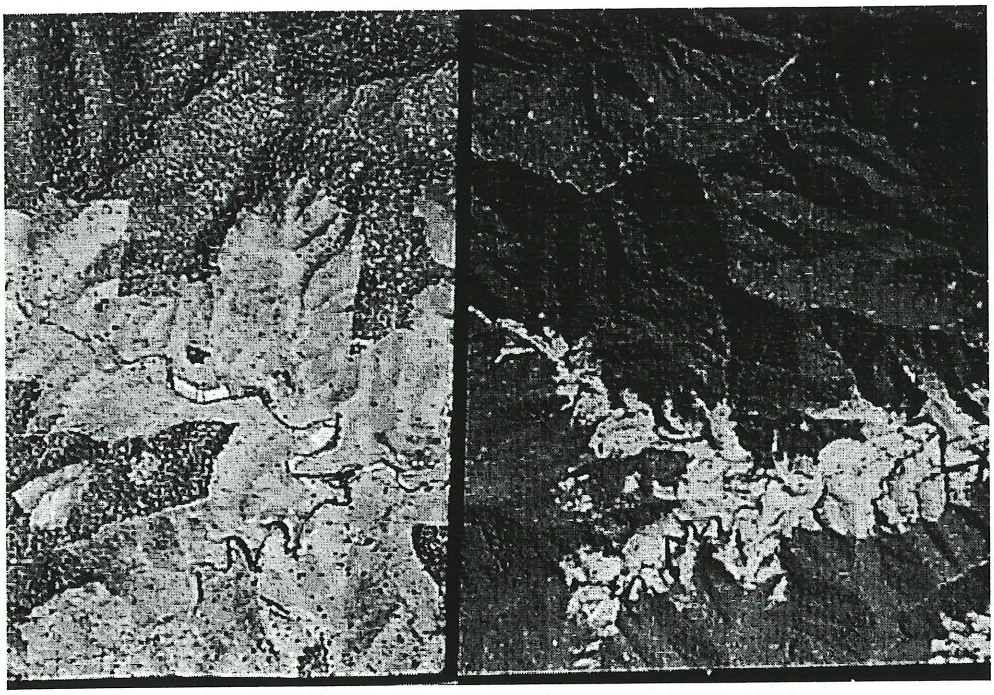

Plate 9: Upper South Arm @ Jaspers Ck., around site S1/2 - 1942 LHS; 1991 RHS

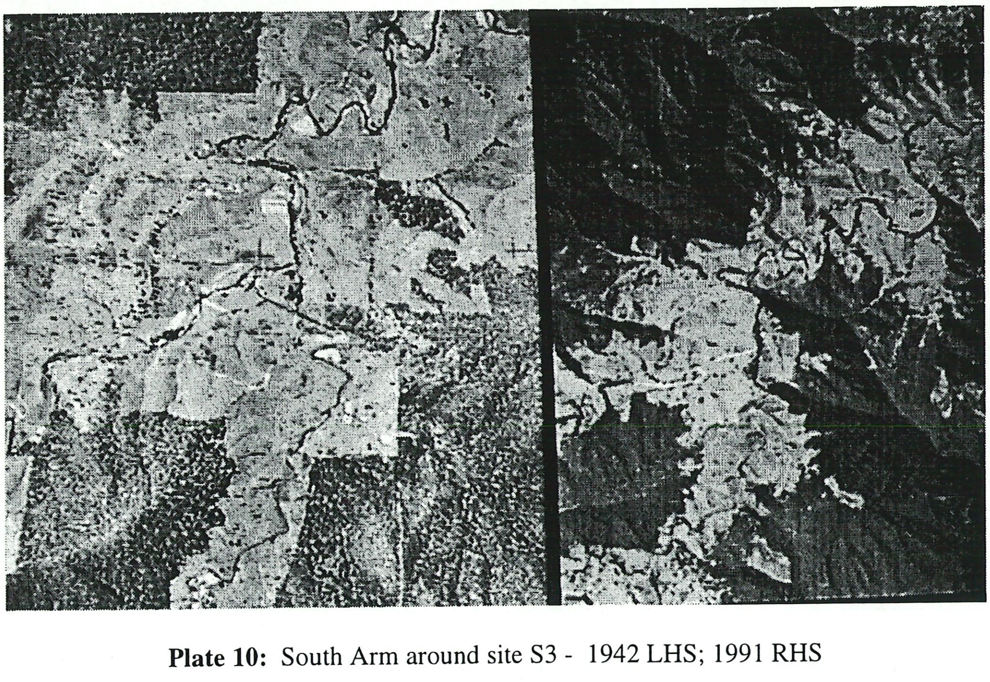

Plate 10: South Arm around site S3 - 1942 LHS; 1991 RHS

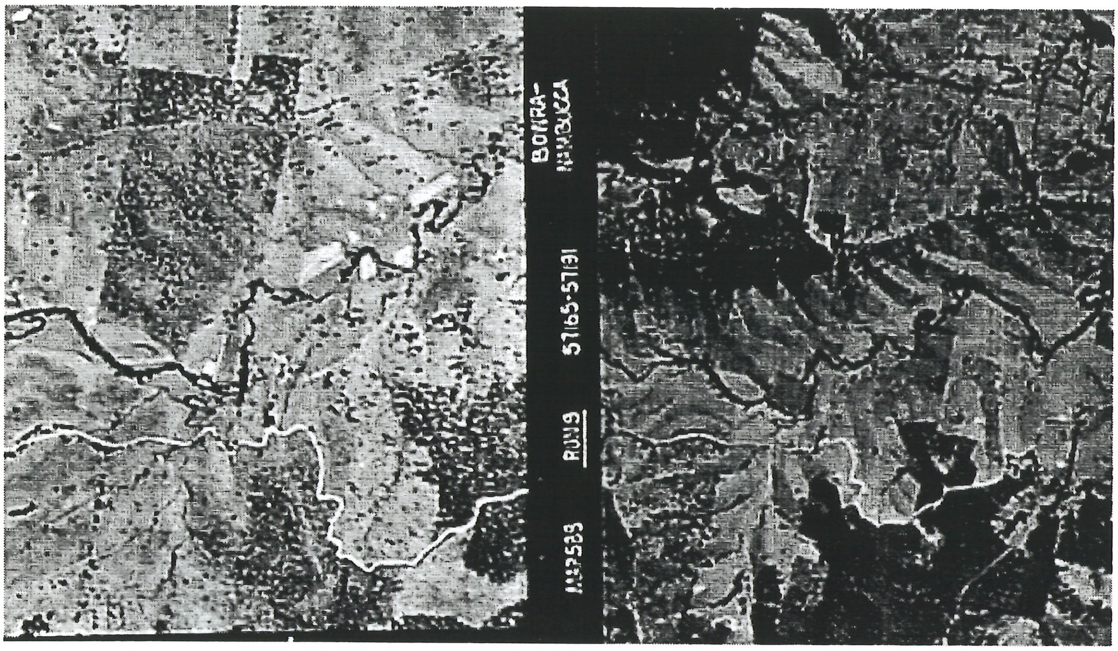

Plate 11: South Arm around site S4 - 1942 LHS; 1991 RHS

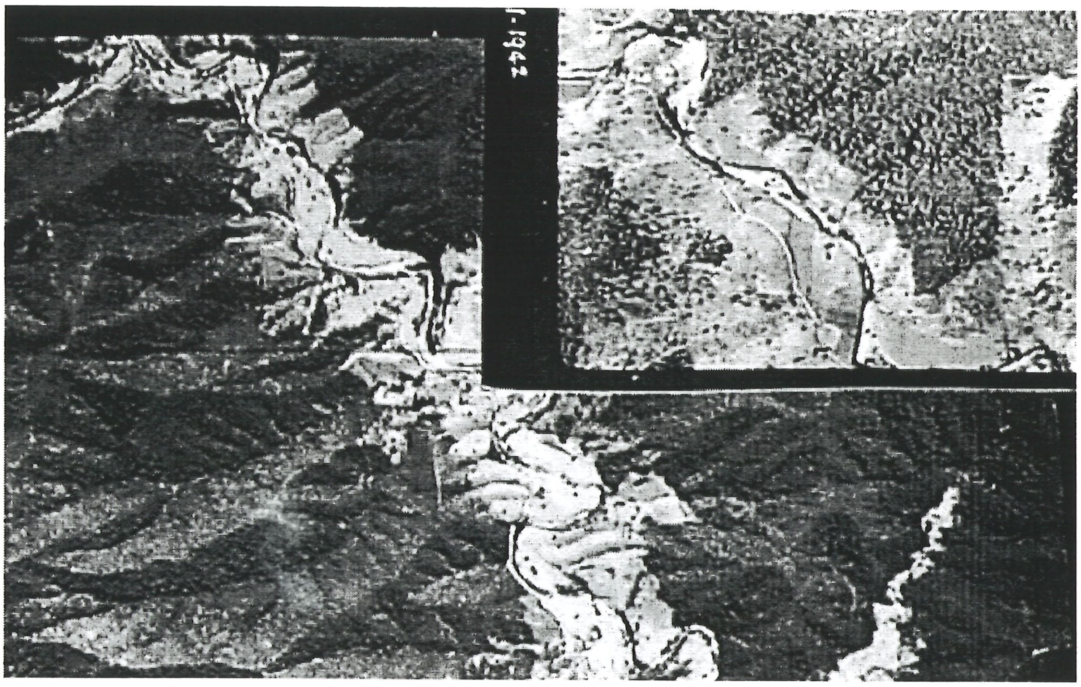

Plate 12: Upper Taylors Arm D/S Thumb Ck. confluence, around site T3 - 1991 LHS; 1942 RHS

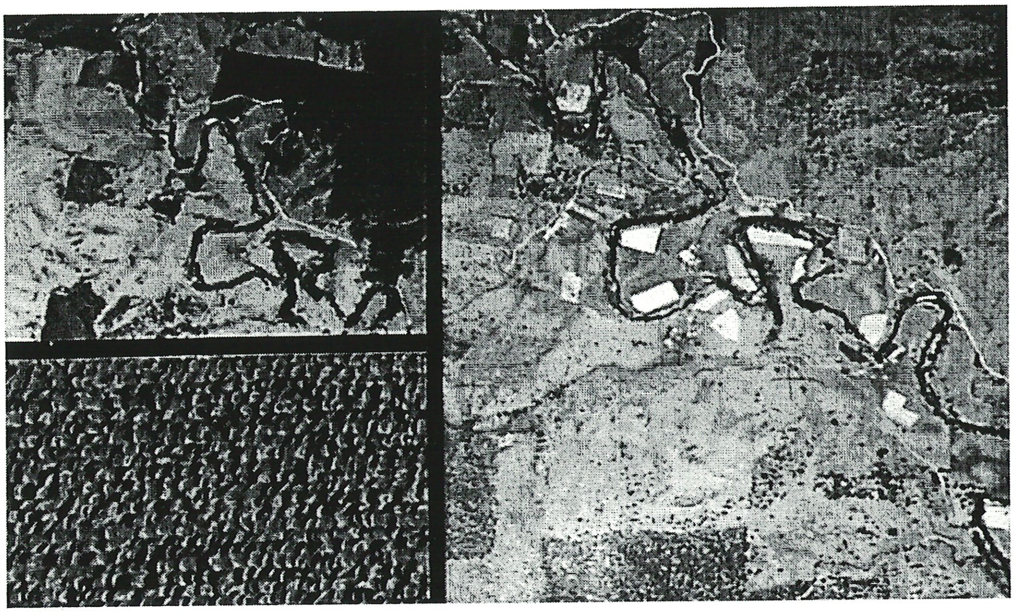

Plate 13: Taylors Arm around site T7 - 1991 LHS; 1942 RHS

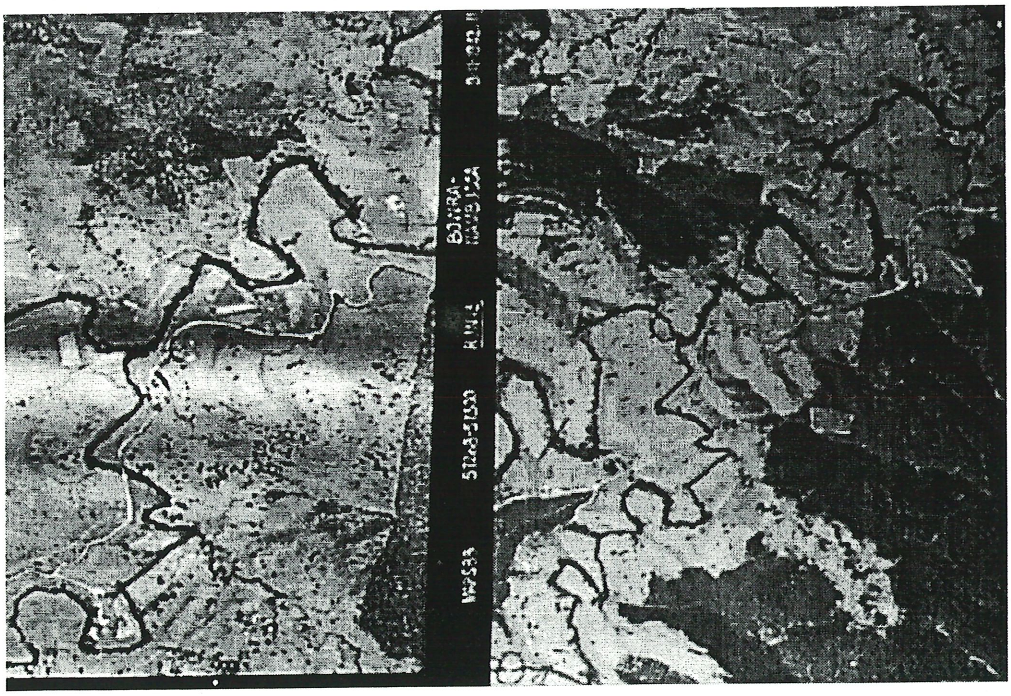

Plate 14: Taylors Arm around site T9 - 1942 LHS; 1991 RHS

Appendix 3 - Landowner Surveys - Riparian Vegetation Issues

Results of surveys in which respondents raised particular *issues regarding vegetation* - by catchment: In addition to comments and questions specifically mentioning vegetation issues, I have included in this collation, comments associated with stock on banks, log sills (artificial woody debris) , and some comments regarding bed destabilisation where it particularly relatd to bank erosion processes. Anonymity has been maintained in this collection of responses. Where observations of changes over time have been made I took the liberty of indicating the length of time respondents have been living on their properties, to provide some context for the comments.

Summary of Issues Raised

- **Responses for which there is apparent universal agreement across the entire catchment:**

  * Large Casuarinas growing on the top of eroding outside bends will hasten bank collapse, and should therefor be removed.
  * Camphour laurels are a pest and should be eradicated
  * Native shrubs such as Tea tree (*Leptospermum brachyandrum*), Bottle brush (*Callistemon viminalis*), and sand paper fig (*Ficus coronata*), which "lay down" in floods, are almost universally considered to be beneficial - although needing management in some places.
  * *Lomandra longifolia* and *L. hystrix* seemed to pretty universally regarded as a beneficial species.

  Virtually everything else is controversial in one way or another!

■ Summary by Sub-catchment

■ **Warrell Ck/Eungai Ck**

Q3 - indicates more vegetation in the middle of the channel than before (resident 59 years)
Q5 - suggests significant bank erosion due to lack of vegetation on Ck. Banks (other than kikuyu)
Q7 - works required : revegetation of Ck. Banks, incl. fencing out stock
Q11/b - suggested indegenous species for revegetation work: water gum, Melaleuca, lemon scented tea tree, weeping paperbark, mat rush, swamp foxtail, feather rush?
Q11/c - eradicate privet and camphour laurel
Q11/c - eradicate: lantana, privet, willow

■ **Deep Ck.**

Q3 - more vegetation in creek now than in previous years (resident approx. 40 yrs.)
Q5 - build up of gravel and vegetation is pushing main stream flow against opposite bank causing extreme erosion.
Q6/b - revegetation works as part of river rehabilitation works
Q6/c - revegetation works failed because vege. did not have time to establish before flood
Q11/a - natives: lilli-pilli, water gums, bottle brush, lommandra espec. NOT Camphour laurels
Q11/b - natives: lilli-pilli, water gums, bottle brush, lommandra
Q11/c - if native and natural, not eradicated but controlled

■ **Buckra Bendinni Ck.**

Q3 - (over last 50 years)... more vegetation - has changed from willow trees etc. to tall trees eg. Camphour laurels. Natural log sills (woody debris) have disappeared
Q3 - (over last 57 years) loss of willow, oak and other spp. + proliferation of camphour laurel and privet
Q4 - a little bank erosion and a few trees falling in the river
Q4 - trees fell over - bank erosion - gravel bars lowered
Q5 - trees fell over and bank erosion
Q10 - lack of correct type in most areas
Q10 - too much vegetation
Q11/a - grass cover used in conjunction with smaller trees would be best served along the stream banks
Q11/a - low trees and grass
Q11/a - willow, oak, river gum and most local natives - grass in some places
Q11/b - grass spp. suggested as most suitable are kikuyu and seteria
Q11/b - willow - the root mass not only filters the water but holds the bank like a mat
Q11/c - camphour laurel and privet
Q11/c - camphour laurels
Q11/c - she-oaks and camphour laurel should be eradicated
Q17 ..... It will be necessary to remove camphour laurel and privet. They poison the land and the water to natural flora and fauna.

- **Upper Buckra Bendenni**

Q3 - (over last 17 years) More she-oaks along and in creek beds. During 90 - 95 drought, I noticed where there were trees and thicker vegetation, the water flow remained above ground, whereas where water was open to the elements, it went below the gravel.
Q3 - small leafed crofton weed appears tp be replacing native vegetation along the creek bed + first level floodplain
Q4 - more erosion of banks that lack vegetation
Q10 - banks without vegetation are worst hit by erosion
Q11/a - As mentioned in response to Q3, I've observed where there were trees - there was water flowing. The trees have naturally occured since I moved onto the property.
Q11/a - Both - the water flows freely over grass and causes little damage, although if the cover is disturbed, grass is undermined quite easily. Tree roots do cause some turbulence of flow and some erosion , but in general hold banks together much longer than if no trees exist
Q11/c - No - unless they are causing obvious problems with water flow or are contributing to major erosion.
Q17 - i) Leave trees to grow along river banks. The root system seems to hold the banks and ensure above ground water flow. ii) Stop clearing areas right up to creek edge. Perhaps leave a buffer of vegetation.

- **South Arm**

Q3 - Jaspers Ck. has native vegetation along the entirety of its banks from its source to where it joins South Arm Ck. So its width does not change much at all, it is well contained.
Q10 - Yes, this has been one of the major contributors to the gravelling up of our creeks and to erosion, siltation etc. I think the most important thing is to stabilise the banks with natives.
Q11/a - Trees, but there are 3 levels of different types of plants and trees that need to be planted. Level A: close to water - native plants and grasses that handle water over them. Level B: a bit further away - native shrubs eg. sandpaper figs, lilly pilly etc. Level C: further from edge - native trees eg. Brush box, red cedar, white cedar, tallowood etc.
Q11/b - (A) bleeding heart, matt rush, sandpaper fig. (B) lilly pilly, brush box, mock olive, native frangipanni, native tamarind, bottle brush. C) White cedar, red cedar, flooded gum, tallowood, iron bark, Morton Bay fig.
Q11/c - When they come up in the middle of the channel and you can see they are going to divert the water towards an unvegetated bank - but hopefully one day when all banks are secure they won't pop up in the middle any more.

Q3 - (over approx. 30 yrs.) More vegetation (Oaks, camphour laurel). Less willows on stream edges. More large dead timber stumps in stream.
Q5 - As long as I can remember, erosion from time to time has happened. We have always tried to take appropriate action to slow it down. Large Oaks have caused some problems.
Q7 - Maybe clearance of logs and approval to poison or remove Oaks & camphour laurel.
Q11/a - As a child there were many willows on edges. I feel this helped fish population. Broad leafed paspalum appears very good although frost.
Q11/b - Willows - trees to be kept small. Canstant planting and pruning required.
Q11/c - YES! Casuarina.
Q17 - Large vegetation from edges to be removed. Smaller trees and grasses be planted in every slump area.

- **Taylors Arm**

Q3 - (over last 40 years) River oaks have gradually increased in number
Q10 - Only a problem in isolated areas
Q11/a - Both grass cover and trees - depends on the location - it is not possible to make a generalisation
Q11/b - Bottle brush, hairy figs & hardwoods further back
Q11/c - She-oaks need control but not necessary to eradicate them. Control Camphour laurel. Another problem in high flood flow areas - need trees that will lay down.
Q16 - The "plant a tree" panacea - some Landcare groups and landholders appear to believe the only solution to the river's problems is to just plant trees.
Q3 - (over last 12 years) Channel narrower since Landcare reveg work.
Q5 - Due to loss of vegetation and other related problems the upper Taylors Arm river has lateral migration and bed degradation
Q11/a - shrubs/rushes - see Alan Raine's species list.
Q11/c - No. Casuarina are an important part of the biomass - They need to be managed.
Q4 - She-oaks fell into stream and caused scouring
Q5 - Because of soft banks along stream and little vegetation, much soil was washed away....as above, many she-oaks fell and caused scouring into banks
Q6 - over 300 native trees & grasses - Lommandra , bottlebrush, tea tree & lilly pillies were planted at base of cliff to slow the flow of stream
Q7 - More vegetation needs to be planted, more fencing off stream from cattle
Q11/a - Sandpaper figs, Bottlebrush, river gums, flooded gums, Lommandra, red cedar, silky oaks, tea trees
Q11/b - as above
Q11/c - Only where they may fall into the stream causing bank erosion
Q3 - Narrower & deeper + less vegetation (over last 13 years)
Q10 - The problem is uncontrolled vegetation
Q11/a - Bottlebrush & grass
Q11/b - Broad leaf paspalum & bottlebrush and other small natives
Q11/c - Yes
Q17 - Clean the water course of unwanted vegetation and gravel. Let the river turn on the slab rock banks and not on the river flats - that will slow the river down!
Q3 - (*amongst other things*)....Vegetation along stream bank is increasing due to instigation of Landcare group.
Q7 - Yes - ongoing fencing for keeping stock out of river & off the banks + massive plantings of species native to this area.
Q11/a - Both - native vegetation peculiar to this area.
Q11/b - Yes - those native to the area on streambank & Lommandra
Q11/c - No - not overall
Q17 - Fencing stock out of river, revegetation of banks with native species + battering down of banks, the use of sills, jacks and groynes as sediment traps etc.....
Q3 - (over last 67 years) Bed lowering, more gravel, more vegetation, less flow.
Q7 - Yes - log sills required to prevent further bed lowering.
Q10 - Stream bank vegetation on my property is adequate
Q11/a - Both grass and trees
Q11/b - Bottlebrush, broadleaf paspalum, Lommandra, willow
Q11/c - Yes

Q3 - (over last 60 years) Shallower, same gravel, same vegetation, same flow.
Q5 - Trees undermined on banks
Q7 - Large Oak trees felled before undermined
Q10 - No
Q11/a - Both
Q11/c - No
Q5 - Yes - because of gravel build up (over last 3 years) where river oaks have been allowed to grow in drought times
Q7 - A) Tree planting to hold alluvial flats B) Remove overgrowth of oaks
Q10 - Yes in areas vegetation needed to stabilise alluvial soil
Q11/a - Both. Large river gums, flanked by bottlebrush, willows, kikuyu and other native river scrub.
Q11/b - as per previous Q
Q11/c - Yes Oaks most definitely
Q10 - Definitely yes - the flats & banks are totally denuded
Q11/a - Trees - prefer endemic species but those with proven bank holding properties
Q11/b - Local Landcare lists should be trialed
Q11/c - If they are a proven problem
Q10 - No
Q11/c - She oaks divert the flow and should be periodically culled
Q6 - Large trees fallen into river during flood. This causes river migration
Q10 - No. Large trees over 6m in height fall into river
Q11/a - Trees with grass cover, bottlebrush, broadleaf paspalum
Q11/b - Taylors Arm willow at water level. Bottlebrush on banks with broadleaf
Q11/c - Remove She-oaks over 6m in height from waters edge.
Q3 - Narrower, shallower, more gravel, vegetation has increased in the last 10 years
Q5 - Mainly initiated through vegetation growing on gravel islands
Q6 - We have done some revegetation & put in a sill to overcome river bed lowering
Q10 - In some areas and a change of vegetation in others
Q11/a- bent trees - bottlebrush types in close. I believe each piece of stream must be assessed. Grass in many cases is enough - in others a combination.
Q11/b - Bottlebrush type small trees, sand paper fig
Q17 - The strategic removal of gravel from known deep water holes that were there but have filled in - This must be accompanied by the use of log sills & vegetation
Q7 - Yes - stabilise banks in several areas, removal of river oaks, tree planting
Q10 - Yes - kikuyu flats with cattle wandering up and down them the edges are not enough to withstand the force of the floodwater
Q11/a - trees, shrubs, grass cover, native grasses
Q11/c - Certainly not eradicated, but they grow in single species forests & this does cause erosion. Mixed with other species they are good
Q17 - Stabilise banks, fencing edges to keep cattle out, planting trees and shrubs
Q5 - Because of neighbours never cutting down river oaks, the river is pushed into my banks
Q6/b - I pushed up gravel & battered the banks and planted willows and river oaks
Q10 - Only if carefully managed
Q11/a - No idea
Q11/b - willows and broad leaf paspalum
Q11/c - Definitely Casuarina has to go
Q10 - Don't know - we never needed repair
Q11/a - Naitive bushes and kikuyu
Q11/c - No - fully grown the hold the banks together and are very pleasant to the eye once they reach the "majestic" size
Q17 - Get the Bowraville district rednecks to learn to live with te greenies s the do in Taylors Arm. Recalcitrant attitude in both parties leads to this eternal bitterness.
Q19 - Leave nature alone in sensitive areas - prudent clearing on the TA, imprudent in the Bowraville district

- **Bakers Creek**

Q3 - Bakers Ck has got shallower, vegetation has become less, flow is same

Q10 - No
Q11/a - As trees get bigger they are bown over or undermined by flood and cause major problems. Small scrubwood are suitable & grass is a good soil binder
Q11/b - Kikuyu grass
Q11/c - Depends on location, flow pattern and bank height
Q17 - Clear timber out of river and remove backed up rubish and soil, gravel, which diverts flood water onto banks

- **North Arm/Nambucca River**

Q3 - (over the last 19 years) The river has got wider and generally lowered its bed. There is more vegetation - the reason, we planted it!
Q6/b - Firstly (1978), banks bevilled - Not successful. (1979) Willows planted & electric fence constructed to exclude cattle. Fences washed away repeatedly, but re-erected. When we could not afford to continue refencing I planted coral trees as the thorns prevented cattle eating them. After each flood I would replant cuttings from either willow or coral trees. I have been working on the river banks for 19 years.
Q6/c - Yes it has been successful as the banks are vegetated and mostly withstand damage by the fast running current.
Q10 - Yes
Q11/a - Hakeas, tea trees, Australian natives, sand paper figs, acacias. I have used willows and coral trees, as cuttings can be used, and this can be done without too much expense. I lost quite a lot of small trees because we had a flood soon after they were planted. Grass alone will not withstand fast current.
Q11/b - Hakea, Callistemon
Q11/c - No - some derelict Casuarinas do cause turbulence - hence erosion
Q17 - Vegetate all river banks
Q19 - I am reasonably happy with conditions on these banks, but there is still more work to be done in some areas - and of course after each flood one must reassess the state of the river and do remedial plantings
Q3 - Steam has increased in width and depth with much more exposed gravel & broken banks. Banks commenced breaking & fallin in the 1950s and 60s with oak trees then regenerating on the gravel bars & eliminating water flows. The gravel has moved into deep corner holes particularly during the last 10-15 years, which has made the river shallower. The big old logs the protruded fromthe banks or were in the water have moved and allowed some of the gravel riffles to deepen.
Q5 - During the 1970 era oak trees germinated & grew along the alluvial bank & reached a height where the soil did not hold them & they commenced falling into the creek & breaking the bank & water then eroded in behind the root systems
Q10 - Various sections will need different types of vegetation. The exposed banks need some form of early? coverage - I believe that grass is the quickest type, but some trees may be required where the stream has pressure mainly in soil
Q11/a - Grass has the potential to cover soil in months where trees give no protection to the banks for years, if they survive. Willows may help if they can be saved from from a flood too soon after planting. In some cases river oaks could be used as pioneer species, but they should be kept to a height where they are not unstable because of the soil they are growing in
Q11/b - Depending on time of year - Millet in early spring with kikuyu to follow, couch grass on gravel & sand. Oaks naturally germinated and kept low, willows in conjunction. Banks must have a coating of soil.
Q11/c - Not in total, but controlled to help during a rehabilitation program. Height must be controlled.
Q3 - Shallower & more gravel, more vegetation, many migration areas. No change in flow or water level
Q4 - Small areas of high bank & vegetation fell into water. Reconstructed area starting to erode again
Q10 - Very seldom. High bank erosion happens regardless of vegetation. The undermining by shifting gravel leaves sodden banks unsupported.

Q11/a - Grass cover prevents surface erosion best. Very seldom is this a problem. Undermining is best supported by small & thick shrubs. Willows, privet, young oaks, tea trees - but cut down once they reach 20 feet high or about 6 inches diameter at butt.
Q11/b - Kikuyu, broad leaf paspalum, Oak, tea tree, willow.
Q11/c - No not eradicated, but controlled. Camphour Laurel are a manace because of their spread, but control is possible.
Q10 - Yes, the loss of vegetation, both by clearing and erosion is a major problem. The sites that are still in relatively good condition are al well vegetated, whilst some of the wort erion is in un-vegetated areas. However, some unsuitable vegetation, for example Camphour laurel and Casuarina when exposed to undercutting are od negative value. Casuarina can of course be of value in the right place.
Q11/a - Depending on distance from the toe of the bank. Some examples: - For waters edge - Lommandra, Callistemon, Leptospermum, Casuarina, - Next row, Cryptocarya glaucescens, ficus coronata - Bank top, Euclyptus grandis, Grevillea robusta. - I have seen examples where grass cover seems to be working, but only on banks that have been batered back. The stream in these areas, to the laymans eye, seems to be wide and shallow. - Casuarina, when there is a prospect of being undercut should be felled, but the root system remain in place
Q11/c - No
Q17 - An oversimplification, but a revegetation of the riparian zone, and possibly some overflow channels should slow the erosion and reduce gravel load overtime. A raising of stream level in appropriate places, by use of sills and weirs, would also assist.
Q10 - Yes
Q11/a - Willows, all grass
Q11/c - Yes
Q3 - Wider, extremely shallower, less water, dieback in willows. The red scheme removed most vegetation from within and edges of stream without any management plan
Q10 - One of the problems. No one thing will fix the river.
Q11/a - Both - even a climbing rose is as good as anything else!
Q11/b - Whatever will grow quickly without being too big and heavy and not too expensive
Q11/c - The Casuarina has its place if managed properly for the area it is grown
Q10 - This is a problem that needs to be looked at in conjunction with deepening water hols so that water is also slowed in high erosion areas
Q11/a - This depends on the particular problem in that parts of the stream will probably need an assortment
Q11/b - Kikuyu is probably the best grass. Care needs to be taken with trees that may form a problem themselves either in damaging the creek or becoming a weed
Q11/c - Yes. She oaks and *illegible* needs to removed from the creek and catchment areas
Q6 - 1978 (banks) bevelled and grassed - unsuccessful. 79 planted willows + fenced off - washed out. Since 1985 planted coral trees - successful.
Q6/b - successful because unattractive to stock, fast growing, extensive fibrous roots spread water flow
Q7 - Western bank requires planting up due to mild erosion
Q10 - Yes - on neighbours side of river
Q11/a - appropriate trees
Q11/b - coral trees have worked here
Q11/c - No
Q17 - Planting of trees to stabilise banks
Q19 - Further planting to be done

- **Sullivans Creek**

Q3 - (over last 11 years) The creek bed has definitely lowered by about 15 cm in more than 75% of the creek on my property + narrower in one bend & a build up of some gravel
Q5 - Cattle on creek & no vegetation in most places
Q7 - stream bed protection & stabilisation + revegetation
Q10 - Yes, they help slow the flow in flood times

Q11/a - Lommandra, leptospermum, watergums, sandpaper figs, + native trees & shrubs. If there is a "nice" sloping bank then there can be grass and trees, but most cases it isn't , so it should be trees & shrubs first , close together.
Q11/b - Lommandra, leptospermum, watergums, sandpaper figs, bottle brush
Q11/c - Depends on where they are. Only if they are causing the creek to divert and cause erosion elsewhere. In most cases definitely not
Q17 - Brush groynes are something that we seem to be having success with. They held up in the May flood. Planting & more planting. Avoid disturbing the banks where possible. Don't change the river course.

- **Lower North Arm**

Q10 - I have observed a great deal of damage caused by trees falling into the water
Q11/a - There are some low growing natives (no more than 10 m). Eucalypts & oaks are problems when they fall. Willows block the stream & the grubs have just about destroyed the willows
Q11/b - grass - kikuyu + natives as mentioned before
Q11/c - yes
Q3 - (over last 30 years) The stream has got shallower with the former deep holes full of gravel. In dry times the water stops flowing as the water disappears under the gravel. Camphour laurel trees have taken over the river banks and are causing great problems.
Q4 - Considerably more river bank erosion than normal. Camphour laurel trees fell off the banks into the river taking much soil with them. They continued to fall for days after flood water receded, blocking the flow of the river.
Q7 - Yes - Landcare group formed. At prsent there are no LAWC personnel to approve work. Gravel shifts need removing and Camphour laurel trees need to be taken from the river & banks
Q10- Some types of trees could be helpful but unfortunately the camphour laurl trees , because of their ability to reproduce are causing great damage where they exist & they are spreading very fast
Q11/a - I am a great believer in grass banks. If you can get grass to grow on the toe of the banks. Trees tend not to allow grass to grow under them and the soil eventually erodes away and the trees end up falling in the river + the banks start to cave in again.
Q11/b - kikuyu, broad leaf paspalum
Q11/c - yes

- **Missabotti Creek**

Q3 - (over last 73 years) River has migrated dramatically, got much wider , much shallower due to infilling of deepholes. Much more vegetation especially on point bars with river oaks casuing stream splitting and more erosion and stream migration. Much less visible stream flow due to gravel build up. Dramatic build up in gravel quantity in stream bed which acts as seed bed for river oaks, which were (prior to 1950s) only along stream banks in odd locations. Stream splits especially when oaks fall in from banks and cause an obstruction in the bed of the river - banks wash & fall in - more gravel - more oaks & so it goes on untill we reach the deplorable position we find the river in today.
Q5 - River oaks allowed to grow to grow to huge proportions on banks due to Water Resources intervention to prevent removal under threat of prosecution for non compliance. Due to leverage of mature trees & undermining in flood situation, trees fall in & water washes around fallen tree & root with resultant break in bank protective vegetation.
Q6 - *amongst other things…..* 6 sills were installed by DWR - method of installation caused erosion on banks not previously existing (failed). In the 60s & 70s - Huge ammounts of public monies were used installing mesh groynes (Shire Council & DWR) - Complete failure - cement blocks & wire ropes a lasting memorial.
Q10 - No except that eroded banks might benefit from planting suitable species. Believe that in my case graded, grassed banks are a better alternative to planting trees. Visual amenity of trees on bank only benefit of trees on bank. Have yet to see one example of trees stabilising a river bank in this area (tens of thousands planted).

Q11/a - As above - grassed and graded banks which worked previously, but which are now anathema to greens controlling DLAWC at present time. Some trees at toe of bank acceptable with proviso that as bank stabilises, trees are removed - otherwise they will become an obstruction in flood situation causing turbulence with consequent erosion around them. Best trees if planted; tea trees and where they already exist bottlebrush. I object to present policy of bringing bottlebrush to catchment where they are not native (Missabotti & North Arm) - future problems because of our fine gravels. Absolute disaster in attempting to establish rainforest varieties in this area due to no canopy cover (frosting)
Q11/b - On grassed & graded banks kikuyu & buffalo grass. Native tea trees and where they are already endemic - callistemon (Do not bring to areas where they do not already grow). Without a single doubt in my mind - an absolute yes (but try and sell this view to our green friends in DLAWC)
Q15 - *amongst other things.....* Huge amounts of money wasted by landcare as a result of planting unsuitable varieties of trees mainly rainforest in frost situation. Tens of thousands have died as a result. Planting trees is not the answer to our problems.

Q3 - (resident 78 years) As our property is immediately above the junction with Missabotti Ck, the widening and deepening of Missabotti Ck bed through excessive gravel extraction has lowered the flood crest level in Missabotti giving Kennaicle a greater fall thus increasing its speed and cutting power for about 300 m causing greater erosion of aluvial flats and freeing more gravel.
Q4 - cut banks back by about 2-3 m in two places and deepened a channel where we used to cross with vehicles but now cannot. Washed young willows and Backhousias away which I was attempting to establish.
Q10 - When we moved here in 1962 there were willow trees established on a shelf about 1 meter above the creek bed with roots visible in the bed holding very well. Privet was getting established which looked to be doing an excellent job also. Willows eventually died and privet started to get undermined, forming small islands.
Q11/a - Trees on the top of high banks are useless as they can be undermined. If a shelf can be created with tyres etc. protecting the lower part of a bank and small species established is ideal. Where the bed is shallow eg. The lower portion of Summervills, a low angle slope of grass consolidated by cattle at least part time, I feel, with floods spreading over low flats is ideal . But where 1950 flood took shortcuts and gravel extraction has created a channel took shortcuts and gravel extraction has created a channel to accommodate most floods within unstable banks, is the major problem.
Q11/b - Strap rushes are ideal.
Q11/c - Casuarinas where they are not in danger of being undermined are OK, but they sow seed onto point bars where the eventually force the creek to meander
Q3 - (resident 80 years) The Nambucca Ck has got wider, more gravel, more vegetation and less flow. Ditto the Missabotti Ck
Q5 - Oak trees are a very big problem on both creeks
Q7 - Yes, banks to be stabilised, oaks to be removed, gravel to be removed on both creeks
Q10 - No
Q11/a - Grass cover
Q11/c - All these types of plant species should be eradicated
Q17 - Remove oak trees from the banks, remove gravel from creeks, remove rubbish growing in the creek to stop water from being diverted into the bank, batter down the banks
Q19 - Build up of gravel, rubbish in the creek and oak trees are the main problem in the Missabotti and Nambucca Ck on my property.
Q3 - Less water especially up stream from us. - Erosion on banks especially where cattle have access
Q4 - No damage along my boundary as vegetation is stabilising the bank
Q5 - Yes, on outside bank where vegetation has been removed
Q6/b - Log sills - River task force 1-2 yrs ago and all have failed leading to a greater shift in gravel
Q6/d - Planting on Missabotti Ck. by the upper Missabotti Landcare group survived.
Q7 - Yes - fencing my neighbours cattle off my bank
Q10 - Yes
Q11/a - Both

Q11/b - Lommandras
Q11/c - No
Q17 - Fence of creek and revegetate

Appendix 5 Significant Floods at Bowraville 1890 - 1979

from NSW PWD (1980) Nambucca River flood history 1890 - 1979

Date	Bowraville (m. above A.H.D. @ Lanes Bridge)
1890 January	9.5
1890 February	10.4
1890 March	11.9
1893 February	10.4
1894 March	8.9
1913 May	8.9
1921 May	9.2
1921 July	9.5
1929 Feb	8.9
1946 March	9.6
1948 May	9.8
1949 August	9.8
1950 June	10.9
1953 March	9.1
1954 Feb	11.0
1959 Nov	9.5
1962 April	9.7
1963 April	8.9
1963 May	9.7
1964 March	9.5
1967 June	8.9
1968 Jan	9.1
1972 Oct	9.5
1974 March	10.7
1977 May	10.0