



The relationship between riparian vegetation, bank erosion and channel pattern, Magela Creek, Northern Territory

Thesis submitted in part fulfilment for Honours Degree, Bachelor of Science, School of Geosciences, University of Wollongong, 2002

Luke Erskine

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## Foreword

Luke Erskine submitted this thesis as partial fulfilment of for the Honours Degree of Bachelor of Science in the School of Geosciences, University of Wollongong, 2002. The work was part of a larger project coordinated by the University of Wollongong titled 'Anabranching river form and process in monsoonal Northern Australia'. The project leaders were Professor Gerald Nanson and Dr John Jansen. *eriss* provided in kind support, accommodation, equipment and some consumables. The fieldwork component of the project which was carried out on Magela Creek, Northern Territory, was completed during the 2001/2002 Wet season.

Luke Erskine was a field assistant for this project, and it was during this fieldwork that he developed the topic for his honours degree. He made a further visit to Magela Creek during the Dry season of 2002 to collect more data. Research staff from *eriss* and *oss* contributed to supervision of Luke's honours research and have taken a keen interest in the outcomes of this research.

The title of Luke's thesis is 'The relationship between riparian vegetation, bank erosion and channel pattern, Magela Creek, Northern Territory'.

Luke graduated from the University of Wollongong in early 2003 with Class II, Division I BSc (Hons).

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Luke Thomas Erskine

A thesis submitted in part fulfilment of the requirements for the Honours degree of Bachelor of Science in the School of Geosciences, University of Wollongong 2002

"The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification."

Signed

Luke Erskine

## Abstract

The relationship between riparian vegetation and flow are poorly understood for rivers in general, and particularly for anabranching rivers. Riparian vegetation along the lowland anabranching section of Magela Creek within the Ranger Mine Lease Area, Northern Territory, greatly influences bank strength, flow hydraulics, sediment erosion and deposition, and bar and island formation. This study presents a comparative investigation of vegetation composition, bank erodibility and flow characteristics for contrasting anabranching and single-thread reaches of Magela Creek. The well-defined anabranching reaches are generally characterised by dense monsoon forest growing on the channel banks and large islands, and the channels are narrow and deep with their steep sides protected by mature tree trunks and thick roots. The forest here is self-propagating with numerous juveniles and is resistant to penetration by fire. The single-thread reaches are generally characterised by relatively low-density melaleuca forest and partly treed and grassy banks. Numerous trees grow within the channel forming multiple bars and small islands. Consequently the channel here is wider and shallower than in the anabranching reaches. Bank hydraulic erodibility on three differently vegetated banks was measured with an instrument specifically constructed for this study and termed a 'hydro jet'. The most resistant banks are protected by a dense melaleuca root mat at the head of bars and small islands around within-channel trees. The next most resistant are the relatively finegrained and steep banks within the anabranching reaches. The grass-lined banks on the single-thread reaches were the most easily eroded of the three surfaces. Velocity fields measured close to these three bank types show that the anabranching banks can withstand very high bank shear, as do the heads of bars, whereas the grassy bank experience least. However, the anabranching reach exhibits bank alcoves that generate strong upstream eddies that, along with the retarding effect of dense island vegetation during overbank flow, restrict channel velocities occurring at greater than bankfull to less than those that occur at below bankfull. Such a velocity reversal does not occur in the less densely treed single-thread reaches and illustrated the significant role played by flow-momentum transfer associated with the densely monsoonforested islands. Clearly, vegetation, bank erodibility and channel pattern are strongly interrelated variables on Magela Creek.

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# Chapter 1 Introduction and Aims

#### **<u>1.1 General overview</u>**

This study investigates the relationship between vegetation, bank strength and sediment erosion and deposition along the mostly anabranching section of Magela Creek. Riparian vegetation appears to play a very important role in defining the character of many fluvial systems, but quantifying the relationship between bank strength, channel form and vegetation proved difficult to achieve. As a consequence, no uniform field method has previously been developed to quantitatively measure the role played by riparian vegetation in influencing channel form. This study presents a quantitative method for assessing the role of riparian vegetation in contributing to the formation and maintenance of multi-channel anabranching reaches along Magela Creek in northern Australia.

The Alligator Rivers Region (ARR), which is located in the tropical north of Australia (Figure 1.1), is drained by the catchments of three major rivers: the East Alligator, South Alligator and the West Alligator Rivers. Magela Creek forms the major left-bank tributary of the East Alligator River. The study area on Magela Creek is located within the Ranger Uranium Mining lease, which has been excised from Kakadu National Park (KNP) (Figure 1.2).

For several reasons this area provides an excellent environment in which to study the effects of riparian vegetation. First, studies have already been performed on the sediment movement characteristics (Roberts, 1991) and on the sedimentary and Quaternary evolution of the Magela Creek (Nanson *et al.*, 1993). Second, Jansen and Nanson (in prep.) are currently undertaking a detailed comparative study of the flow hydraulics and sediment transport of multi-thread and single-thread channels of Magela Creek. Finally, a study of the current morphodynamics of Magela Creek, coupled with the present study of the riparian vegetation and its interaction within the system, will provide information that may benefit environmental management of the Kakadu World Heritage area.

A significant focus of this study is the development of a simple field method for quantifying the immediate local effects of vegetation on bank strength. This was used to examine the broader issue relating the role of vegetation on the occurrence of well-defined multi-thread channels in contrast to single-thread channels.



Figure 1.1: Location of Alligator Rivers Region, northern Australia. Source: Erskine and Saynor (2000).



Figure 1.2: Location of the study area (dashed line) and the two detailed study reaches at the downstream single-thread and upstream anabranching sites (shown in red). After: Mount Brockman 1: 50, 000 Topographic series, Australia, Sheet 5472-1 (1997).

### **1.2 Riparian vegetation**

Riparian vegetation is increasingly being recognised for its importance in influencing the hydrology and morphology of fluvial systems (Hack and Goodlett, 1960; Smith, 1976; Charlton *et al.*, 1978; Hickin, 1984; Hey and Thorne, 1986; Thorne, 1990; Ikeda and Izumi, 1990; Millar and Quick, 1993; McKenney *et al.*, 1995; Hupp and Osterkamp, 1996; Fielding *et al.*, 1997; Abernethy and Rutherfurd, 1998, 2000, 2001; Rowntree and Dollar, 1999; Tooth and Nanson, 2000; Gurnell *et al.*, 2001; Bendix and Hupp, 2000; Webb and Erskine, 2001). The study of the influence of riparian vegetation on fluvial geomorphology is complicated by a variety of factors, several of which are briefly discussed below.

First, Hickin (1984) contends that fluvial geomorphology is unable to deal with interactive processes, such as vegetation, that are not easily quantifiable or physically and statistically manipulable. That is, vegetation interactions are difficult to scale and model in a flume, but many areas of vegetation-related fluvial processes are poorly understood and require further analysis. Second, the growth of vegetation is composed of a complex series of stages and a large number of life forms, which make their quantification difficult (Thorne, 1990; Hupp and Osterkamp, 1996; Huang and Nanson, 1997; Rowntree and Dollar, 1999). Last, vegetation operates in a number of ways and in certain positions it can act to increase channel stability (for example through root reinforcement of sediment and by lowering the threshold for erosion by retarding flow) and in others it affects open flow hydraulics in a manner which may increase channel instability (Hupp and Osterkamp, 1996; Abernethy and Rutherfurd, 1998, 2000, 2001; Rowntree and Dollar, 1999). The role of riparian vegetation influencing flow (Parsons, 1963; Hickin, 1984; Smith et al., 1990), root reinforcement of banks (Abernethy and Rutherfurd 2000, 2001), bar formation (Fielding et al., 1997), island formation (Gurnell et al., 2001) and bank failure (Thorne, 1982, 1990) have all received attention in the literature. There has been no particularly successful technique employed within the variety of disciplines that study rivers, including fluvial geomorphology, hydrology, sedimentology, biology and engineering, to quantify the effects of vegetation on bank strength.

Both living and dead large woody debris (LWD) that can influence erosion and deposition along rivers (Keller and Swanson, 1979), for LWD can act to increase or decrease channel stability. Tree-fall may cause a significant level of bank erosion, but if debris remains in situ the trunk can protect the bank and propagate several new species in order to stabilise the section. Conversely, LWD can cause local scour and increase bank and bed erosion of the bank and bed (Keller and Swanson, 1979; Graeme and Dunkerley, 1993; Webb and Erskine, 2001). However, a gap in the literature exists and this study therefore develops a method of quantifying the role of vegetation and attempts to establish the effects of vegetation on flow hydraulics and bank strength within contrasting anabranching and single-thread reaches of Magela Creek.

#### **1.3 Flow hydraulics and vegetation**

The distribution of vegetation within fluvial settings has important implications for open channel hydraulics and flow resistance. Relationships exist between vegetation and flow velocities, with dense vegetation increasing flow resistance along the banks and on the floodplains. In open-channel flow, velocity is one of the most sensitive and variable properties because of its reliance on numerous inputs. The nature of the change in velocity is important because velocity influences the erosion, deposition and transportation of material (Knighton, 1998). Flow resistance has a large influence on velocity through its interaction with both fluid flow and the channel boundary.

Dense tree spacing has the effect of significantly lowering flow velocities due to increased flow resistance and subsequent form roughness. Conversely, wide spacing between trees can lead to localised increases in velocity and thus significant erosion and flow disturbance (Parsons, 1963; Smith et al., 1990; McKenney *et al.*, 1995).

It is hypothesised that the flow interactions of vegetation combined with high flow variability are important factors in the formation of multi-channel reaches within the lowland anabranching section of Magela Creek. There is a large amount of flow variability within Magela Creek with many overbank flows each year and these are followed by prolonged periods when Magela Creek ceases to flow. Thick monsoonal vegetation located on the large islands appears to be protected from fire and is able to propagate a high density of immature species. The high flow resistance introduced by dense vegetation, coupled with immature tree species establishment, may

substantially lower the in-channel and overbank flow velocities in the anabranching reaches. This may reduce the erosive potential of the flow and increase the deposition of fine material held in suspension. In areas where trees grow within the channel bed, such as the single-thread reaches of Magela Creek, vegetation may increase flow disturbance through localised increases in velocity and thus decrease the effectiveness of bank top vegetation in determining the geometry of the channel (Nanson and Huang, 1999).

#### **<u>1.4 Previous work using jet testing devices</u>**

As a means of quantifying the resistance of vegetated surfaces to particle detachment, a hydro jet was devised to measure the relationship between vegetation and hydraulic erosion. Bank erosion within the study reach is predominantly through fluvial detachment of grains from the bank surface. Therefore, a hydraulic test of the resistance of particles to detachment was seen to be the most appropriate means of relating vegetation type and bank strength.

Two previous studies using a jet of water to test soil parameters were conducted by Sherard *et al.* (1976) and Hanson (1991). Sherard *et al.* (1976) used a pinhole jet for identifying dispersive soils. The erodibility of the soil was not a parameter being tested in their study, although it was the first study that used a jet of water as a tool for measuring soil properties. More recently, Erskine *et al.* (1995) have used the methodology described by Sherard *et al.* (1976) to measure the dispersion of soils on the Wingecarribee River.

Hanson (1990, 1991) was an agricultural engineer who was interested in the study of scour and head cut migration in spillways. His jet testing was thus substantially different to that employed here and was related to the depth of scour and not the amount of material eroded under the impinging jet.

#### **1.5 Controls on anabranching rivers**

Anabranching rivers remain the last of the four main river types to be investigated in detail (Nanson and Knighton, 1996). Single-thread meandering, braided and straight rivers have all received significant attention and the factors governing the occurrence of anabranching rivers are now becoming a focus of attention (Nanson and Huang, 1999; Jansen and Nanson, in prep.). Although vegetation is recognised as an important factor influencing anabranching rivers (Knighton and Nanson, 1993; Nanson and Knighton, 1996; Wende and Nanson, 1998; and Tooth and Nanson, 1999) there has been no attempt to truly quantify the influence of riparian vegetation on their formation and development. Tooth and Nanson (2000), while not quantifying the effect of vegetation, have detailed the relationship between vegetation and anabranch formation for a central Australian river.

Anabranching rivers are characteristic of large areas of the Australian continent (Nanson and Huang, 1999). Worldwide they occur in a vast array of geomorphologic settings from steep boulder-bed headwaters through to low-gradient flood out systems, whereas in Australia they have been described by various authors (Schumm, 1968; Riley, 1973; Riley and Taylor, 1978; Rust, 1981; Rust and Nanson, 1986; Knighton and Nanson, 1993; Nanson and Knighton, 1996; Schumm *et al.*, 1996).

Anabranching rivers are also present in the ARR of the Northern Territory, Australia. The study area for this thesis is situated within the lowland anabranching section of Magela Creek below the Arnhem Land escarpment (see Figure 1.2). Here a number of authors have described vegetation as playing an important role in determining channel change (Williams, 1979, 1984; Roberts, 1991; Nanson *et al.*, 1993; and Erskine and Saynor, 2000;), but none of these studies has attempted a quantitative analysis of the effects of vegetation on bank erosion and sediment deposition.

Riparian vegetation is believed to be an important factor in the formation of anabranching channels along the Magela Creek. The key conditions identified as important for the formation of anabranching rivers include a resistant bank material relative to flow strength, flow variability and lateral stability (Knighton and Nanson 1993; Nanson and Knighton, 1996). The banks of Magela Creek consist of predominantly fine to medium sands, which are essentially cohesionless. The bank

strength leading to lateral stability appears to be provided by vegetation lining of the banks that in the presence of relatively low stream powers promotes anabranching (Nanson and Knighton, 1996).

#### <u>1.6 Aims</u>

The primary aims of this study are:

- To quantify the geomorphic significance of bank vegetation on the lowland, sand bed, anabranching section of Magela Creek, and to describe and map the distribution and densities of riparian tree species.
- To examine the differences in vegetation type, bank erodibility and flow hydraulic variations between a well-defined anabranching reach and an essentially single-thread reach, in order to evaluate the possible significance of vegetation in the formation and maintenance of these two distinctive stream patterns.

#### **1.7 Research Design**

The problem of quantifying bank strength was addressed by designing a water jet that enabled the hydraulic erosion of sections of natural river bank. The *hydro jet* tests the relationship between the vegetation on the bank, the associated root strengthening of the surface and thus the sediment erosion resistance to particle detachment. A number of different surfaces were tested (tree, grass and root mat) and the resistance to erosion of each surface was determined. A hydraulic method was devised to test the erodibility of vegetated surfaces, as there are two dominant mechanisms that erode banks. First, mass failure, which involves rotational slips and slab failure. River bank susceptibility to this form of erosion is dependent on the bank properties, geometry and structure (Thorne, 1982). Mass failure is not a form of erosion within the anabranching reach of Magela Creek. Hydraulic erosion is the other mechanism that erodes banks and involves detachment of particles from the bank surface and subsequent entrainment. It also involves scour at the bottom of the banks leading to oversteepening and resultant gravitational failure of the bank. The detachment of individual particles was determined to be the main bank erosion mechanism within the study reach. The hydro jet method was developed to quantitatively measure the resistance of the differently vegetated bank surfaces to granular detachment.

Several vegetation community parameters were measured in order to determine the vegetative difference between the multi-thread and single-thread reaches. For both reaches, vegetation transects were sampled, tree densities measured along the bank tops, and the vegetation was mapped. Vegetation distribution, density and location within each reach have been compared. The presence and height from base of fire scarring on mature trees was also measured in order to determine the significance of burning on channel pattern within the area.

The effect of vegetation on flow was measured using velocity gauging performed during the Wet season. The vegetative influence on velocity was measured adjacent to a tree-lined bank, grass-lined bank and around a vegetated bar with dense root mat at the head. Floodplain and within-channel velocities were also gauged at the anabranching and single-thread sites.

Site selection was based on the occurrence of a well-defined anabranching reach and an essentially single-thread reach within close proximity. Both were also chosen because they were being investigated for a study on the flow efficiency of anabranching systems (Jansen and Nanson, in prep.). This meant that considerable additional useful data were being collected at the same time.

Erskine *et al.* (2001) recommended a research project to determine the importance of riparian vegetation and LWD within the Swift Creek catchment as part of the activities by the supervisory authority for the Jabiluka uranium mine. The project outline concluded "the mechanisms actually operating in the channels flanked by riparian forests in the Swift Creek catchment need further quantification" (pg. 32). This project has now been completed and is currently being written up (Dr W. Erskine, Office of the Supervising Scientist, personal communication, 2002). Given that Magela Creek is close to Swift Creek, a similar study of riparian vegetation on the anabranching section of the Magela Creek will add considerably to our understanding of the role of riparian vegetation in controlling channel form and process within the lowland areas of Kakadu.

#### **1.8 Thesis Outline**

The thesis has been structured in the following manner:

Chapter 2 provides a review of the relevant literature describing aspects of anabranching rivers and riparian vegetation, and the role of riparian vegetation on bank strength, flow hydraulics, bar formation, island formation and bank morphology. It also reviews what work has been done using instruments similar to the hydro jet.

Chapter 3 presents a description for the Magela Creek catchment, including study reaches, along with climate and seasonal rainfall patterns, geology, regional geomorphology and hydrology.

Chapter 4 describes the methods used in this study. A detailed description of the design and use of the hydraulic erosion jet is provided along the methods of vegetation analysis. Other methods used in the study are also described.

Chapter 5 presents the research results.

Chapter 6 discusses these results in the context of the importance of the riparian vegetation in the formation and development of an anabranching system and summarises the most important findings in relation to previous work and to the role of riparian vegetation in determining bank strength and anabranching.

# Chapter 2 Literature Review

#### **2.1 Introduction**

While the effect of riparian vegetation on hydraulics and geomorphology have gained increasing recognition over the past few decades, quantification of these effects has remained a difficult problem and has thus received relatively little attention. Vegetation significantly influences channel morphodynamics, and for anabranching rivers in particular, such effects are far from well understood. Definitions of anabranching rivers and the causes of their formation are reviewed, with reference to the presumed effects of vegetation on their development and maintenance. Literature describing the role of riparian vegetation and LWD, the effects of fire on vegetation and erosion, flow hydraulics, the importance of vegetation root systems and bank strength is then reviewed. This is followed by a summary of previous work that has utilised hydro jet indices to measure the erodibility of soils. Lastly, the literature on bar and island formation is reviewed.

#### 2.2 Channel patterns and anabranching rivers

Meandering, braided and straight rivers have all been studied in detail. The factors governing the occurrence and maintenance of anabranching regimes have become the focus of considerable recent investigation (Nanson and Knighton, 1996). A river that is in a state of dynamic equilibrium exhibits an ability to adjust its channel pattern, cross-sectional geometry, slope and roughness in order to balance the available sediment load with an ability to transport this load (Mackin, 1948). Why do rivers anabranch? The persistence of anabranching systems both temporally and spatially indicates that in certain situations they are likely to exhibit considerable advantages over their single-thread counterparts (Nanson and Knighton, 1996).

For alluvial channels, Nanson and Huang (1999) performed an analysis of basic hydraulic relationships including flow continuity, slope, roughness and several sediment transport functions. Their study suggested that in situations where there is little or no opportunity for the system to increase slope, conversion from a wide, single channel to a semi-permanent, multiple channel form can lead to a reduction in total width and increase average flow depth, hydraulic radius and velocity. This conversion can enable the system to maintain or enhance water and sediment throughput, even overriding moderate increases in channel roughness. It was found that in certain situations anabranching systems appear to be closer to exhibiting the most efficient sections of flow for the conveyance of both water and sediment than are equivalent wide, single channels at the same slope (Nanson and Huang, 1999).

However, not all anabranching systems are hydraulically efficient. Once formed, some channels may, due to an inability to change with time, continue to operate despite increasing inefficiency (Nanson and Huang, 1999). The finding that they are sometimes not efficient is particularly interesting considering that vegetation has been linked to the formation and maintenance of some anabranching systems due to its influence on bank strength, and it may also cause the system to resist change over time. Therefore, a quantitative analysis of the role of vegetation on the formation and maintenance of anabranching reaches will enable the above finding to be thoroughly investigated.

#### 2.2.1 Causes of anabranching

Anabranching rivers are recognised as one of the four main river types together with meandering, braided and straight. Nanson and Knighton (1996) defined an anabranching river as a 'system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull' (pg. 218).

A number of different anabranching river patterns have been categorised by Nanson and Knighton (1996). These were classified on the basis of stream power, fluvial morphology, sedimentology and fluvial processes. They found that hydraulic, physiographic, geological and botanical conditions appear to play a role in influencing anabranching river types.

The development of anabranching rivers is dependent on the combination of hydraulic and sedimentary conditions (Smith and Smith, 1980; Knighton and Nanson, 1993). Nanson and Knighton (1996) found that anabranching rivers can be found in a variety of environments and that climate itself does not appear to be a determining factor. There appears to be a number of factors that play an important role in the

formation of anabranching rivers. These include: low flow strength, low bank erodibility, lateral channel stability, sediment supply that exceeds the rate of onward transport, and a high degree of flow variability (Smith and Smith, 1980; Knighton and Nanson, 1993; Nanson and Knighton, 1996; Makaske, 2001).

Magela Creek was classified as a type 2, sand-dominated, island-forming anabranching river by Nanson and Knighton (1996). Anabranch stability in the fine to medium sands of the area requires low specific stream powers, a high proportion of the flow overbank and riparian vegetation that is believed to provide considerable protection to the banks, bars, islands and floodplains with tree roots penetrating well below the level of the river bed. It is shown that even during major flood events in the area, erosive energy remains low because of the relatively low channel gradients. Under such conditions, both stream flow and bed-material sediment load are concentrated along sections of relatively narrow, deep channels rather than spread over less efficient, wider and shallower channels that are partially obstructed by trees growing within the channel (Nanson *et al.*, 1993).

The dense riparian forest appears to be essential for lateral stability, without which the system would probably form braided channels (Nanson *et al.*, 1993). Quantitative vegetation assessment is yet to be undertaken for Magela Creek. The section of Magela Creek containing the study site has been classified as anabranching rather than anastomosing (a low gradient, fine grained anabranching system). It is characterised by lateral stability, steep-sided banks in the anabranching reaches, sandbed channels, reinforced banks with dense root mat, long individual channels between points of bifurcation and confluence and well-defined and stable (vegetated) islands with marginal levees forming central depressions (Roberts, 1991; Nanson *et al.*, 1993; Erskine and Saynor, 2000).

Nanson and Knighton (1996) concluded that a highly seasonal or extremely episodic flow regime is an important characteristic for the formation of anabranching rivers. For Magela Creek, they found that this was certainly the case, with the seasonality of rainfall contributing to high flow variability with long periods of no flow during the Dry season followed by many floods during each Wet season.

The stabilising effect of bank vegetation is believed to be able to exert an influence over channel pattern. The level of bank resistance to erosion is relative to specific stream power or the bank shear stress. Nanson and Knighton (1996) found that the banks of type 2 streams are mainly sands, but the resultant effects of

significant riparian vegetation in combination with low per unit stream power results in the lateral stability of these systems.

The role of climate, base level and floodplain sedimentation rates, as causes of anabranching remain unclear (Smith, 1973; Makaske, 2001). Knighton and Nanson (1993) and Makaske (2001) found that climate itself does not appear to be a significant factor although Makaske (2001) suggested that climate and geology are important external controls of the processes leading to the formation of such rivers. He also found that certain controls, especially vegetation, seem to differ with climate. For Magela Creek, it appears as though the location of the system within the seasonally wet tropics of northern Australia may have elevated the importance of the monsoon riparian vegetation in the formation and maintenance of anabranching channel sections.

Nanson and Knighton (1996) found that there appears to be a distinction between erosional systems and accretional anabranching systems. Erosional systems excavate channels within the floodplain while accretional systems build islands within, or floodplains around, existing channels (Nanson and Knighton, 1996). It is not known at this stage whether the development of channels within the anabranching reach of Magela Creek is erosional or accretional in origin (Roberts, 1991 and Nanson *et al.*, 1993).

#### 2.3 Role of riparian vegetation

Over the last three decades riparian vegetation has received increasingly significant attention for its role as a control over channel form and process within fluvial systems (e.g. Smith, 1976; Charlton *et al.*, 1978; Hey and Thorne, 1983; Hickin, 1984; Hupp and Osterkamp, 1985, 1996; Thorne, 1990; Abernethy and Rutherfurd, 1998, 2000). Vegetation interacts within fluvial systems by influencing flow hydraulics and the sedimentology and stability of the banks, channels and floodplains (Parsons, 1963; Smith *et al.*, 1990; Thorne, 1990; Hupp and Osterkamp, 1996; Bendix and Hupp, 2000). Studies on the empirical relationship between channels lined with dense vegetation (e.g. trees and shrubs) and channels of similar dimensions lined with grass only, show that the well-vegetated channels are on

average 0.5-0.7 times the width (Hey and Thorne, 1983, 1986; Huang and Nanson, 1997, 1998).

Hack and Goodlett (1960) were possibly the first authors to relate geomorphology, vegetation and hydrology. They found that distinct types of forest were identifiable within the Little River Basin, based on the relationship between plant ecology and topographic position. Disturbances, such as hillslope runoff and bottomland flood, were also found to influence the dominance of tree species.

Smith (1976) concluded that banks with significant vegetation were up to 20,000 times more resistant to erosion than similar banks with no vegetation.

Hickin (1984) was one of the first researchers to identify that riparian vegetation plays an important role in river channels and detailed it as relating to the following five mechanisms:

- 1) By increasing flow resistance
- 2) By increasing bank strength
- 3) Bar sedimentation
- 4) Formation of log jams
- 5) Concave bench deposition.

Erskine *et al.* (2001) also believe that a number of other important mechanisms should be added to this list including channel contraction, bed stabilisation by log and root steps and pool formation. Thorne (1990) found that vegetation effects are complex and depend on factors such as vegetation species, location and density, as well as channel width, depth and sediment size.

Brooks and Brierley (2002) were able to identify three key mechanisms of vegetation that allow it to mediate the equilibrium channel condition:

- 1) Mechanisms that physically resist change
- Mechanisms reducing the impetus for change (lowering energy within the system)
- Mechanisms enabling channel recovery following deviation from an equilibrium condition.

Tooth and Nanson (2000) concluded that vegetation could exert a significant influence on river hydrology and geomorphology. The influence of vegetation is complex and not yet fully understood. In terms of how the vegetative influence should be assessed, Tooth and Nanson (2000) highlight that a series of quantitative, processbased studies of the role of vegetation in influencing river hydrology and geomorphology are required. The other problem recognised by Hickin (1984) and Tooth and Nanson (2000) is that there are difficulties in quantifying or statistically manipulating the influence of vegetation.

Huang and Nanson (1998) concluded that a detailed quantitative analysis of the size, density, location and even health of bank vegetation could provide a high level of prediction for bank strength. The importance of vegetation in stabilising the banks of rivers has proven difficult to assess (Hickin, 1984; Nanson *et al.*, 1995; Nanson and Knighton, 1996).

McKenney *et al.* (1995) found that the stem density, stem diameter, and the position of the woody debris in the flow field influence sites of erosion or deposition. Additional factors that they identified as affecting the ability of vegetation to provide stability to the bank sediment included root strength and density, particle size and bank height.

At habitat spatial scales, woody vegetation in and along stream channels can have substantial effects on channel form and process by increasing the roughness of flow, altering sediment erodibility, and by providing woody obstructions to flow (Keller and Swanson, 1979; Hickin, 1984; Thorne, 1990).

Hupp and Osterkamp (1996) deduced that the position of a plant species within the riparian zone is due to its adaptation to the prevailing environmental controls within that fluvial setting and competition with other riparian species. This process of natural selection leads to the development of characteristic riparian vegetation patterns.

A number of native trees, such as *Melaleuca argentea*, readily coppice when flood damaged, thus allowing them to significantly increase the extent and stability of riparian forest systems. Fielding *et al.* (1997) identified this species as able to 'engineer its own environment' by deflecting currents, stabilising banks and building sand and gravel bars. Evidence also supports the contention that the presence of vegetation, such as melaleucas, when growing *within* channel has a destabilising effect on a reach. However, this may also lead to localised bank instability due to local increases in flow velocity. The channel bed roughness introduced by the vegetation growing in the channel is able to override the bank vegetation in determining channel geometry (Huang and Nanson, 1997; Rowntree and Dollar,

1999), resulting in eddying and possible destabilisation of individual trees as well as the adjacent bank (Lawler *et al.*, 1997).

Regular periods of high water levels during the Wet within the study area play a significant role in determining the species present within the riparian zone, similar to that described in Northern America by Hupp and Osterkamp (1996). Trees that possess the ability to develop adventitious roots and survive periods of inundation are most advantageous. That is, trees that can still survive even though their basal roots are periodically water logged. The monsoon forest associated with the large islands of the anabranching reach is composed of different tree species to the single-thread sites, which contain more open woodland species.

#### 2.3.1 Large woody debris

Keller and Swanson (1979) found that the high degree of roughness within channel provided by LWD combined with a dense understorey of vegetation could act to significantly influence channel morphology and stability. Webb and Erskine (2001) identify that LWD and riparian vegetation increase roughness by providing flow resistance and dissipating energy, which reduces boundary shear stress.

Graeme and Dunkerley (1993) establish that the existence of trees growing within the channel bed, and associated LWD jams, can increase flow retardance and consequently decrease bankfull discharges and velocities by up to 50%.

One of the more important roles of LWD within fluvial systems is the role it plays in creating and stabilising sites for the establishment of immature vegetation (Fetherston *et al.*, 1995; Abbe and Montgomery, 1996). The distribution of LWD within Magela Creek could influence the stability of channel planform and in areas where there is significantly higher tree densities it would be expected that a high loading of LWD would occur.

#### 2.3.2 The influence of floods on vegetation distribution

Floods play at least a three-fold role in influencing the distribution of areas for vegetation establishment and the survival of riparian plants (Bendix and Hupp, 2000):

- 1) Most riparian plants germinate in alluvium that is deposited during floods
- 2) Floods may create colonisation sites by destroying pre-existing vegetation
- The occurrence or lack of floods subsequent to germination may determine whether seedlings survive to maturity.

For Magela Creek, where rainfall is particularly seasonal and floods are an annual occurrence, the majority of trees within the riparian zone must be well adapted to flood and their survival and regeneration strategies must involve an ability to cope with inundation, prolonged root saturation and flood damage through erosion and scour. The ability of immature species to grow at the same rate as the water level drops and the ability to cope with long periods of inundation and possibly scour in order to reach maturity is an important adaptation for the successful growth of melaleucas highlighted by Fielding *et al.* (1997).

Bendix and Hupp (2000) found that the presence of a given species on a particular landform might permit a considerable presumption concerning the hydrogeomorphological setting characteristic of the fluvial landform. The highly seasonal climate of the ARR ensures many annual floods (~ 12 overbank floods) within the catchment. Therefore, the riparian trees are significantly adapted to inundation and the associated problems of waterlogged roots, flood damage and seed dispersal. The adaptations of tree species within the Magela Creek system may exhibit an association with the setting, as described above by Bendix and Hupp (2000). Distinct areas of vegetation zonation would thus be able to be related to the prevailing hydrogeomorphological conditions.

#### 2.4 Effects of fire

Nanson *et al.* (1993) found that riparian vegetation and monsoon forests of the ARR are the important factors stabilising the sand bed anabranching streams. From a management perspective, Erskine and Saynor (2000) have recommended that the floodplain vegetation should not be burnt to ensure it continues to protect the sandy stream banks from the erosive forces of large floods. This is particularly important in the early Wet season as the seasonal grasses are unable to regenerate quickly. They also found that burning of the riparian vegetation and monsoon forest will lead to increased sedimentation in the billabongs and wetlands of the area.

Responses to fire include reductions in the amount of soil cover, lower soil binding strength of roots, decreased protection by foliage from rain drops, and increased surface run off leading to accelerated erosion and changes in soil characteristics, such as hydrophobicity (Prosser and Williams, 1998; Evans *et al.*, 1999; Beeson *et al.*, 2001; Johansen *et al.*, 2001). Wildfires increase the risk of accelerated soil erosion through the decreased protection provided by organic litter, ground vegetation and canopy cover. A reduction in surface ground cover significantly reduces the threshold for the initial movement of sediment (Prosser and Williams, 1998).

Burning of the KNP area is conducted mostly over the late Dry season as a management tool by both the traditional owners and Parks Australia North (PAN) (Russell-Smith, 1995; Evans *et al.*, 1999; Russell-Smith *et al.*, 2002). Published data suggest that more than half the lowland area of Kakadu is burnt each year (Braithwaite and Estbergs, 1985; Press, 1988). Most plant species and vegetation types in KNP are well adapted to persistent burning as a consequence of interactions with fire extending over some millions of years, well before the arrival of Aboriginal people about 50,000 - 60,000 years ago. As a consequence, many woody savanna species possess attributes that allow them to survive after burning, such as thick protective bark, or if aerial stems are killed, the capacity to regenerate from woody tissues held at or below ground level (Russell-Smith, 1995).

One aim of PAN is to reduce the frequency, extent and intensity of wildfires within the KNP and to protect species and habitats particularly sensitive to fire (ANPWS, 1986). This is very beneficial for the KNP area, but it does not necessarily protect similar land adjacent to the Park, such as the mining lease.

One of the management practices undertaken by PAN is to employ early Wet season burns of the grass *Sorghum intrans*, which typically grows to approximately 3 metres. Grasses such as this species provide one of the main woodland and riparian grass fuels. The early Wet season burns are conducted in order to eliminate both the standing (dry) fuel and new shoots (Russell-Smith, 1995).

Vegetation that is relatively fire sensitive on the other hand includes monsoon rainforest patches. Barlow (1994) found that monsoon vegetation shows a high degree of sensitivity to fire. Burning of these areas within the riparian zone may lead to a decrease in vegetation diversity, and seed dispersal and regeneration patterns may as a result be adversely affected. Thus, the channel planform could be influenced by fire, if the fire was significantly large enough to reduce the vegetation cover and destroy existing mature trees.

Floodplains comprise mostly open herbaceous communities and fringing paperbark (melaleuca) forests and currently present the major challenge for fire management in KNP (Russell-Smith, 1995). Melaleucas and other woody species with superficial root systems are particularly susceptible to being killed by subsurface fires that burn in the humic soil surface (Russell-Smith, 1995). Williams (1984) also found that soil fire may be a contributing factor to tree loss in the Magela system.

With a significant build-up in floodplain fuels combined with a period without fire, it may be anticipated that particularly large fires will occur within the area. A significant fuel loading was observed on the right bank of the study site in June (2002) and during August a hot fire destroyed the immature species and groundcover and burnt many of the mature tree species along the island between the middle and right channels of the well-defined anabranching reach. Fire management, if it is to occur at all, needs to be more organised, in order to leave a mosaic of burnt and unburnt areas and thereby maintain the diversity of growth forms and species, and provide protection to the banks of local sand-bed stream from erosion and a diverse habitat for local fauna.

#### **2.5 Flow hydraulics and vegetation**

McKenney *et al.* (1995) found that single trees or widely spaced trees within the flow often lead to localised turbulence and velocity increases upstream and along the sides of the tree. The change in the velocity of flow forms a horseshoe vortex and scour around the obstruction. Deposition often occurs downstream of the vegetation on the lee-side of the vegetative effect.

For two main reasons, flow resistance induced by vegetation can dramatically change during a flood. First, if a tree falls into the channel due to undermining or wind throw (McKenney *et al.*, 1995), and second, if with an increase in flow depth, the flexible stems of the vegetation bend downstream (Thorne, 1990). Within channels, submergent aquatic vegetation can increase flow resistance, decrease effective cross-sectional area and promote erosion and deposition (Watts and Watts, 1990). Bendix and Hupp (2000) found that floods play an important role in that they can erode and uproot trees and also create new areas of sedimentation, which are ideal
sites for opportunistic species to colonise these areas. Successional change may then return the disturbed location back to its former state.

In the initial periods of overbank flow, there is a considerable level of flow retardation afforded by densely vegetated banks. The bank tops within the study reach of Knighton and Nanson (2002) were heavily treed and, as a result, they found that there was a large degree of flow retardation at the channel-floodplain interface. This was directly attributable to the bank-side vegetation. They found that as they moved away from the bank-top vegetation (mainly trees), the floodplain vegetation became much less dense and more flexible. Thus, the effect on flow retardation is reduced.

Huang and Nanson (1997) found that vegetation growing in the bed of a channel can significantly increase channel roughness by retarding flow. They found vegetation growing in the bed could have a greater control over the channel geometry than bank vegetation.

Anabranching channels require a resistant bank material and a high degree of bank strength relative to the erosive energy of the stream. The dominant erosion process within the Magela Creek is fluvial erosion. Abernethy and Rutherfurd (1998) found that in areas where fluvial erosion is the dominant bank erosion process, the flow resistance due to vegetation becomes crucial to channel stability. Therefore, vegetation interactions with flow (shear stress and velocity) include an increase in roughness and a decrease in velocity. It is believed that anabranching channels interact with flow in a manner which is vastly different to single-thread channels. The differences in flow relationships between these areas awaits investigation.

# 2.6 Roots for anchorage and bank strength

Root systems provide plants with anchorage to the substrate and with riparian trees this function is important for producing bank stability (Abernethy and Rutherfurd, 2000, 2001). However, regardless of the bank texture vegetation increases bank stability only to the rooting depth. If bank height exceeds the depth of roots, the weight of the vegetation may in fact increase the probability of bank failure (Thorne, 1990).

Abernethy and Rutherfurd (1998) found that it is the rooting depth of the bank-top vegetation versus the depth of the critical failure plane that is the important

channel-scale issue for the mass stability of banks. For their study reaches the banks were much steeper and higher than for Magela Creek where vegetation growing along the banks is far more successful at providing stabilisation towards the base of the bank. Abernethy and Rutherfurd (2000, 2001) focussed on quantifying the increases in sediment strength due to root reinforcement. They found that plants enhance bank strength by reducing pore-water pressures and by directly reinforcing bank material with their roots. Their study did not investigate the hydraulic or surface effects of vegetation, instead dealing with the subsurface soil strength interactions. In order for subsurface interactions to be important, the effect of vegetation at the bank surface where the erosive forces (shear stress) are highest must be fully understood. Abernethy and Rutherfurd (2000) found that the difficulty in determining the influence of vegetation on bank properties lies in understanding how the vegetation modifies bank hydrology, flow hydraulics and bank geotechnical properties. They found that it is the position of the tree on the bank and their root distributions throughout the bank that are important influences on riverbank mass failures.

## 2.7 Bank and soil erosion

Lawler (1992, 1995) subdivided the main factors involving bank erosion into three main groups. The first group consists of subaerial processes that include microclimate (mainly temperature, not important in tropics) and bank composition (especially the silt/clay percentage of bank material). Second, is mass failure. This process is not important within the anabranching section of Magela Creek, because bank heights and angles are insufficient.

Last, is a range of fluvial processes that erode banks through direct particle detachment from the bank surface and subsequent fluvial entrainment. The influential factors on fluvial bank erosion include stream power, shear stress, secondary currents, local slope, plan form, bank composition, vegetation and the level of moisture content in the bank.

The banks of Magela Creek are non-cohesive (mainly fine to medium sands) and Lawler *et al.* (1997) identify that the character of erosion on non-cohesive banks relates to individual grain detachment and subsequent entrainment. They found that the stability of sediments is dependent on the relative balance of forces acting on

individual particles. Their study identified that bank erosion and stability were influenced by bank vegetation in practically all aspects.

Huang and Nanson (1998) found that many channels exhibit a transport-active bed and yet maintain relatively stable banks. Magela Creek has a supply of sediment that exceeds onward transport, but maintains a high degree of lateral stability. Huang and Nanson (1998) found that in response to variations in bank strength (a function of bank sediment and vegetation), banks differ in their resistance to erosive forces and thus exert considerable influence on alluvial channel geometry.

Stocking (1994) found that vegetation is believed to be the single most important factor in soil erosion control in the tropics. In terms of rainfall, vegetation cover provides erosion protection to the soil by the interception of raindrops and by absorbing their kinetic energy. She also found that, provided the vegetation is maintained above a certain level of cover (50-60%, but varying according to type of cover and soil), the interactive process between the soil and the plant are sufficient to limit erosive forces.

The effects of vegetation on soil erosion control can be subdivided into three groups. First, height of the vegetative cover above the ground surface is important in influencing the size of droplets. Second, the height of the canopy due to tall growing trees may reduce the level of ground cover completely. Last, there exists a complex interaction among vegetation, slope, soil type, and erosion. There are a number of interactive processes between a plant and soil that affect the degree of erosion including the physical binding of the soil by plant roots and stems, detention of runoff by plant stalks and organic litter and vegetation interaction with soil, all leading to better soil bonding and structure and improved infiltration (Stocking, 1994).

## 2.8 Water-jet instruments

Sherard *et al.* (1976) developed a pinhole dispersion test for the purpose of analysing the nature of dispersive soils. Whilst not directly dealing with the dimension of bank strength, this study was the first to utilise a water jet as a means of measuring soil properties.

Hanson (1990) has been one of the few authors to perform soil strength testing using a water jet erosion instrument. Hanson used a site-specific, submerged water-jet erosion device. He was not concerned with the amount of material eroded, instead he was looking at the depth of scour. As an agricultural engineer, he examined the erosion resistance of grassed spillways gully headwalls. Therefore, while his methodology was somewhat different, his approach had similarities to the current study. Hanson varied the velocities of his jet and the period of time over which he applied the jet of water to his selected surfaces. He found that the erosion beneath the impinging jet, expressed as the depth of erosional scour divided by time, could be related to the velocity of the jet, a time function and a soil parameter to give a jet index. Hanson's results indicated that as scour occurs, the shear stresses imposed by the jet along the soil boundary decrease, but these initial conditions represented by a smooth boundary play an important role in the scouring process.

Hanson (1991) recommended the jet index as a method for providing a standard uniform procedure for characterising the erosion resistance of soils. He believed that it would be best applied to soils as a means of a standard uniform procedure for characterising the erosion resistance of soils.

Hanson (1990) identified the need to research the erosion rates for bare and vegetated soil materials in natural settings. He stated, "a procedure to determine the erodibility of a soil from site to site is necessary" (pg. 130). The bank sediments along Magela Creek do not appear to vary to any great extent. As a consequence bank strength may be measured directly with some type of erosion jet to determine the effect of vegetation on this relatively uniform material.

## 2.9 Bar and island formation

Nanson and Knighton (1996) found that islands along anabranching rivers form either by excision due to channel avulsion from floodplain, or develop by within-channel deposition or by prograding distributary channels building deltas or splays. It was also found that islands within an anabranching system are approximately at the same elevation as the floodplain, and usually remain for decades or centuries, support well-established riparian vegetation, and have relatively stable banks.

Gurnell *et al.* (2001) explored the relationships between topography, sediment and vegetation. They found that riparian vegetation and LWD make an active

contribution to the process of island formation and persistence through time. They found that "river islands have the potential to greatly enhance biodiversity within the riparian zone" (pg. 31). This may be especially true for Magela Creek, given the levels of floodplain and bank disturbance due to annual burning of large areas.

Usually, large and small islands and ridges separate the channels of anabranching reaches. The large stable islands on Magela Creek are commonly vegetated with thick dense monsoonal vegetation and they are considerably more stable and influential at effecting flow than are the single-tree bars. The bars are formed by vegetation growing in the channel bed and have a small-scale influence over the hydraulics at a site, especially on the adjacent banks, whereas the islands have a profound effect on the channel hydraulics.

A significant factor influencing the formation of bars and perhaps islands is the presence of within channel vegetation growing on available surfaces. Fielding *et al.* (1997) detailed the role of *Melaleuca argentea* in the formation of bars. This species is present at both study sites of Magela Creek and has adapted to its environment through a number of structural and growth modifications.

## **2.10 Summary**

Many studies have detailed the effects of vegetation on various aspects of fluvial geomorphology, although there has been little work on the influence of vegetation on the formation of anabranching rivers and there has been very few attempts to quantify the effects of vegetation on bank strength for these rivers. An appropriate field-based quantitative method for comparative measurements of bank strength in relation to vegetation has not been devised.

The methodology and results of field analysis into the effects of vegetation on bank strength, flow, sediment deposition and erosion, as well as the possible effects of vegetation on anabranching and single-thread channels along a reach of Magela Creek, are described in the following chapters.

# Chapter 3 Catchment Description

# **3.1 Location**

Magela Creek catchment is located within an area known as the ARR in the tropics of northern Australia (Figure 1.1). Magela Creek flows northwards for a distance of approximately 90 km from its headwaters to its confluence with the tidal reach of the East Alligator River. An anabranching section persists for approximately 24 km on a pediment surface downstream from a bedrock gorge in the Arnhem Land escarpment, and upstream from Mudginberri Billabong. Below the billabong the system floods out onto channel-less wetlands before entering the East Alligator River via a reformed channel. The study area is situated in the intermediate section adjacent to the Ranger Uranium Mine, and extends from Sandy Crossing to slightly upstream from the junction between Gulungul and Magela Creeks (Figure 1.2). This area lies within the mining lease excised from the KNP for the Ranger Uranium Mine, thus, the rules and regulations for work on the lease had to be obeyed. There will be more on the limitations associated with this in a later section.

## 3.2 Climate

The climate of the ARR is monsoonal and dominated by the Wet and the Dry seasons. Thus, the area is often called the seasonally wet tropics (Wet season duration 4.5 to 7 months) (Hoatson *et al.*, 2000). The region including KNP is included in the summer-rainfall tropical climatic zone, which is characterised by heavy periodic rains and generally hot and humid conditions from November to March, and essentially dry and mild to warm conditions from April to October (McQuade *et al.*, 1996). The mean annual rainfall at Jabiru Airport was 1485.3mm for the period from 1971-2000 (Figure 3.2) (Bureau of Meteorology, 2002). At Jabiru, 92% of the average annual rainfall is recorded during the Wet season months of November to March (McQuade *et al.*, 1996). Rainfall variability in the summer rainfall-tropical climatic zone is low



Figure 3.1 Location of study reaches and geomorphology of the Magela Creek catchment. Source: Roberts (1991)

to moderate, but high daily totals are recorded during tropical cyclones. On average, one tropical cyclone affects the Northern Territory coast per year and these may lead to extended heavy rainfall periods (McDonald and McAlpine, 1991). Their impact at inland Jabiru is much less frequent, with a tropical cyclone occurring approximately once every 10 years.

The majority of precipitation occurs during the Wet season, but it can be further subdivided into two distinctly different rainfall patterns. The first period of the Wet season (November and December) is characterised by a period of high intensity, short duration (30-60 minutes) convectional storm cells. These storms form above the Arnhem Land escarpment and are usually less than one kilometre in diameter (Uren, 1990). This is the period where vegetation cover is at its lowest due to seasonal burning. A tropical cyclone or large rainfall duration during this period would be likely to cause significant erosion.

The formation of the monsoonal trough over far north Australia during the latter months of the Wet (January to March) forms the second phase of rainfall. The storms associated with the monsoonal trough are less intense than convectional rainfall, but are more extensive and of longer duration (Uren, 1990). Vigorous vegetation establishment during this period and its protective effects typically leads to rainfall causing less erosion.

The highest mean-monthly maximum temperature of 37.4°C occurs in October and the lowest of 31.2°C in June. Pan evaporation for the catchment averages 2618mm per year, exceeding mean annual rainfall by 1133 mm (Bureau of Meteorology, 2002).



Figure 3.2: Rainfall histogram from Jabiru Airport (Bureau of Meteorology, 2002).

# **3.3 Geology**

#### 3.3.1 General

The ARR is dominated by two main geological formations. The first is the Pine Creek Geosyncline while the second is the Kombolgie Subgroup. The Pine Creek Geosyncline comprises Lower Proterozoic metasediments overlaying an Archaean basement, and extends from Rum Jungle in the west to Oenpelli in the east (see Figure 1.1 for these locations) (Needham, 1988). The metasediments of the Pine Creek Geosyncline were deposited under predominantly shallow marine conditions in an intracratonic basin some 200,000 km<sup>2</sup> in area. Igneous intrusions of basalt, dolerite and granite occur throughout this unit (Stuart-Smith *et al.*, 1979).

The Arnhem Land plateau is an outcrop of quartz arenite (both ferruginous and non-ferruginous), basalt and tuff. It forms resistant plateaus and gorges of the Arnhem Land escarpment country. This unit was formerly known as the Kombolgie Formation, but has since been redefined as the Kombolgie Subgroup (Carson *et al.*, 1999). The Kombolgie Subgroup extends from western Milingimbi across the East Alligator River, through central, northern, southern and eastern Mount Evelyn and south to northern Katherine. The subgroup unconformably overlies the granitic basement units of the Nimbuwah Complex. The age of this unit is believed to be Palaeoproterozoic (Stratherian) (Carson *et al.*, 1999).

The Koolpinyah surface persists throughout most of the lowlands of the ARR as an extensive pediment. It is composed of unconsolidated to weakly cemented coarse quartz sands and minor conglomerate. The sands most likely formed as fan deposits, with the material being derived from Kombolgie Subgroup sandstone, Mesozoic sandstone, siltstone, claystone and Early Proterozoic metamorphics (Needham, 1988).

#### 3.3.2 Magela Creek catchment

The geology of the Magela Creek catchment is shown in Figure 3.3. The Creek is silt-starved due to geological provenance, dominated instead by sandy bedload derived from the Kombolgie Subgroup and consequently there is very little fine sediment in the floodplain (Roberts, 1991). The upper catchment is composed of the Kombolgie Subgroup and this gives way to the lowland area with Tertiary age Koolpinyah sediments flanking the contemporary channel. Underlying the Creek and its floodplain are part of the Lower Proterozoic Koolpinyah surface and it contains a high proportion of clays with very little coarse sediment (Nanson *et al.*, 1993). The Creek has almost completely infilled the trench cut into the Koolpinyah surface alluvial infill that is concentrically older both laterally and with depth (Nanson *et al.*, 1993).

## 3.4 Regional geomorphology

The ARR has been described as consisting of three major physiographic units: 1) highly resistant Kombolgie Subgroup escarpment, 2) the weathered Koolpinyah surface (essentially a pediment) that forms gently undulating lowlands, and 3) the largely estuarine sediments of the seasonally-inundated floodplain (Nanson *et al.*, 1993). Erskine and Saynor (2000) add to these, 4) the Arnhem Land plateau and 5) the non-estuarine alluvial plains.

The Arnhem Land escarpment varies from 30 to 330 m in height and represents the break between the upland Arnhem Land plateau and the lowland alluvial plains (Galloway, 1976). The Kombolgie sandstone is very resistant to erosion and the escarpment retreats episodically by block fall and then remains stable



Figure 3.3: Geology of the Magela Creek catchment. After: Alligator River 1:250,000 Geological Series, Australia, sheet SD53-1, 2<sup>nd</sup> edition (1983). Note: the Kombolgie Subgroup has not been updated and is listed as the Kombolgie Formation.

for centuries with Roberts (1991) calculating the rate of scarp retreat as being in the order of 0.02-0.2 m per 1000 years. The catchment area upstream of gauging station GS8210009 (GS 009) is  $600 \text{ km}^2$ . The Arnhem Land plateau comprises  $430 \text{ km}^2$  of this area with the remaining 170 km<sup>2</sup> consisting of lowland alluvial plains and pediments (Roberts, 1991).

The Koolpinyah surface is a very old and stable surface topped in places with river terraces and floodplain (Nanson *et al.*, 1993). The extensive undulating lowlands and pediments formed between the escarpment and the floodplains are composed of this material (Erskine and Saynor, 2000).

The anabranching section of Magela Creek begins downstream from Bowerbird Gauge where Magela Creek leaves the escarpment, and ends when the system floods out into the wetlands downstream of Mudginberri Billabong. The Creek flows through a broad and shallow section of valley stripped of the Kombolgie Subgroup sandstone that is cut into the Koolpinyah Surface with low-angle (<2%) side slopes (Roberts, 1991; Nanson *et al.*, 1993). The shallow trenches incised into the Koolpinyah Surface by rivers flowing across its surface, are occupied by sandy river channels, floodplains, river terraces, palaeochannels and wetlands (Williams, 1979; Nanson *et al.*, 1993; Erskine and Saynor, 2000). This section of the Creek contains the study reach.

The system floods out into the permanent wetland area at the downstream end of Mudginberri Billabong and covers an area of approximately 150 km<sup>2</sup>. The permanent wetland area is supplied with water during each Wet season and at peak flow water enters the East Alligator River.

## 3.5 Hydrology

The section of Magela Creek located above GS 009, shows a greater variability in annual runoff than in annual rainfall (Nanson *et al.*, 1990). The maximum flow discharge recorded at GS 009, for the period from 1971-2001 was 1690 m<sup>3</sup> s<sup>-1</sup> in February 1980 (see Figure 3.3) (Northern Territory Department of Infrastructure, Planning and Environment, 2002). Nanson *et al.* (1993) found that for Magela Creek, floods with recurrence intervals of 2, 10, 50 and 100 years have discharges of approximately 450, 1200, 2400 and 3100 m<sup>3</sup> s<sup>-1</sup> respectively. Floodplain

inundation occurs approximately 12 times per year for a total of 40 days above bankfull flow which is achieved at a discharge of ~ 40 m<sup>3</sup> s<sup>-1</sup> (Northern Territory, Department of Infrastructure, Planning and Environment, 2002). The Holocene trench is generally 110-190 m wide and extends up to 370 m close to Mudginberri Billabong (Jansen and Nanson, in prep.). The 2-year recurrence interval is approximately 10 times the bankfull discharge. Therefore, Magela Creek experiences a high degree of flow variability and this appears to be one of the most important aspects involved in the formation of anabranching rivers. The majority of annual flow is passed during the Wet, with 80 % during the wettest months (December to March) and the Creek ceases to flow during the Dry season (approximately 44 days per year) (Northern Territory, Department of Infrastructure, Planning and Environment, 2002). The sandy channels remain dry and the only permanent water is contained within several large billabongs (e.g. Mudginberri). The large amount of bare rock surfaces and thin soil, combined with the almost seasonal pattern of burning, promotes surface runoff that is usually rapid (Nanson *et al.*, 1993).



Figure 3.2: Maximum annual floods from 1972-2001. Note: Bankfull discharge is ~40 m<sup>3</sup> s<sup>-1</sup> (Northern Territory Department of Infrastructure, Planning and Environment 2002).

# 3.6 Exotic fauna

Buffaloes were introduced to northern Australia between the 1820's and 1840's. The removal of buffaloes began in 1979 and today very few remain (Hoatson *et al.*, 2000). Since the eradication of feral buffaloes from the KNP, feral pigs have remained as one of the major management issues in the park. During the Dry season of 2002, pigs were observed to be playing a significant role in the removal of root material from the lower portions of the banks within the study reach.

# Chapter 4 Methods

# **4.1 General Overview**

The current research project examines the links between vegetation, bank strength, erosion and deposition along the lowland anabranching section of Magela Creek. Data on the hydrological, geomorphological and vegetation characteristics of the study areas were collected over two trips, during the Wet and Dry seasons of 2002. Conducting the study over the Wet and Dry seasons allowed for different perspectives to be obtained on the interactions between vegetation, stream flow and fire and it allowed for field refinement of experimental techniques.

The change in vegetation composition and its subsequent effects on sediment strength and flow is hypothesised to be a governing factor in the formation and maintenance of well-defined anabranching reaches, compared to more poorly defined single-thread reaches along Magela Creek. The quantification of a relationship between vegetation and bank strength was obtained by designing a hydraulic erosion jet to test bank and bar erodibility. The approach consists of 6 stages: selection and classification of the bank, taking a pre-erosion photograph, placement of the catcher on the bank and the erosion jet application, collection of the sample, taking a posterosion photograph, and laboratory analysis of the sample.

## 4.2 Vegetation sampling and mapping

The main tree and shrub species in the area were sampled in the field for the purpose of identification, which was mainly performed using the 'Field Key to the native trees and shrubs in the Jabiru area' (Brennan, 1992). Dr. Kym Brennan, *eriss* staff and the 'Plants and Trees of the Northern Territory' (Brock, 2001) were also consulted for the identification of sampled species.

Identification and mapping of all species within the riparian zone was carried out for the upstream anabranching and downstream single-thread study sites. This was performed using an aerial photograph as the base map for the anabranching reach as there were no fixed points. For the single-thread reach, the bars and major trees within the reach were individually surveyed in relation to the suspended cable as the fixed point.

Quantitative vegetation transects were constructed across four surveyed profiles. These were located at the downstream single-thread study reach, upstream single-thread, upstream anabranching study reach and downstream anabranching site. See Figure 4.1 for the location of the two detailed study sites and the four vegetation transects. The position of transects was chosen to illustrate the cross-sectional vegetative differences between the anabranching and single-thread study sites. Each profile was extended approximately 4-5 plots (20-25 m) from the distal extent of the floodplain in order to measure the vegetation boundary between riparian species and woodland species. At 5 m intervals along each cross-section, a 4 m wide (therefore 20  $m^2$ ) plot was marked and each mature tree (over 2 m in height) within each plot was identified, along with its base diameter, breast height diameter, height, percentage canopy cover, and assessed for general health and presence and height of fire scars. Other important parameters that were calculated for each plot included: percentage ground cover, number and type of immature tree species and other important characteristics of the site, such as canopy width of dominant species, presence of LWD and height of understorey grass.

The density and basal area coverage of trees along the banks of the upstream anabranching and downstream single-thread study reaches were measured using the point-centred quarter method as outlined by Mueller-Dombois and Ellenberg (1974) (see Figure 4.2). Ten point-centred quarter measurements were taken along each bank at the single-thread site (40 points on each bank) and 5 point-centred quarters on each bank at the anabranching site (20 points on each bank, 40 points for each channel). The line of the bank was followed at a distance from the bank that varied between sites to allow tree measurements to be made on the channel side. A tape measure was extended along the bank and at 10 m intervals at the upstream anabranching and 15 m intervals at the downstream single-thread, a four-point measurement of the distance to the nearest tree in each quadrat was calculated (Figure 4.2). Care had to be taken not to measure the same tree twice and to leave a sufficient gap on the channel side to allow for trees to be measured. For each tree, the base and chest diameter were recorded, as well as the distance from the centre point of the plot.



Figure 4.1: Detailed vegetation mapping and transect locations. Source: Airesearch Mapping, Jabiluka, Run 2 032-046, 29/8/97.



Figure 4.2: Point-centred quarter tree density method. (after: Mueller-Dombois and Ellenberg, 1974).

## **4.3 Hydraulic erosion jet**

The hydro jet was constructed using a standard 7-litre capacity 'Hills Supa Garden Sprayer'. The jet apparatus consists of a manual hand pump that creates the water pressure in the reservoir. The pressure of the jet when released was measured using a 'WIKA' 0-60psi glycerine filled water pressure gauge fitted to the hose just below the pressure release valve (Figure 4.3).

The shape of the jet being discharged onto the bank was standardised by aligning a mark on the nozzle head with one on the shaft. This procedure allowed for constant flow intensity for the eroding jet of water for each application.

During each application the pump pack was filled with exactly 5 L of water and pressurised to 30 psi. The changing volume of water in the reservoir was found to determine the duration of the flow pressure and therefore the volume of water was set at 5 L for all tests and applied over a set time period of 30 seconds. As a consequence the jet maintained a constant flow that did not fluctuate between measurements. The jet of water was discharged onto the bank from a distance of 30 cm. The jet was directed onto the bank horizontally and at  $90^{0}$  to the alignment of the surface. It was applied to the bank over a fixed surface area in a Z wash-down pattern from side-to-side, top to bottom, so that the eroded material was moved into the catcher.

The sediment catcher was designed using two  $45^{\circ}$ , 150 mm PVC pipes (see Figures 4.3, 4.4 and 4.5). These were glued together and sealed at the bottom using a 150 mm cap. The top of the catcher was removed in order to allow the jet to spray through to the bank. The circular collar at the face of the catcher ensured the surface area being tested remained constant. The surface area of the catcher was 177 cm<sup>2</sup>. The face of the catcher was cut at an angle of  $45^{\circ}$  in order to accommodate the wide variety of bank angles being tested. No banks in the study area were  $90^{\circ}$ , therefore the catcher had to be designed to allow the bank sediment that was liberated by the impinging jet to be caught and retained. The period of erosion was fixed to a time of 30 sec, which allowed the sediment to be retained in the catcher without overflowing.

The test surfaces were not pre-saturated during the Dry season because banks had uniformly low moisture contents and were regarded as being similar.

A detailed explanation of the methods used in the hydro jet testing is now provided. It was decided to present these as a series of progressive steps showing the details of the methods used from field to laboratory:

#### Step 1 Bank selection and classification

The first step in the process was to select a bank for testing that contained the dominant vegetation type, with a slope greater than  $45^{\circ}$ . There were three main types of surfaces that were found within the study area. Tree-lined banks were tested, as they were representative of the anabranching reach, whereas grass-lined banks and root mat surfaces were tested as they are more representative of single-thread reaches. Prior to testing each location, a detailed site description was completed. The description included: bank angle, bank shape, bank orientation, type of vegetation present on the bank, identification of main species, distance to base of main species from test location, position of hydro jet test relative to drip line, density and thickness of surface roots and mean root size and root mat.



Figure 4.3: The pump pack with pressure gauge attached is on the right. The catcher standing in the upright position is in the middle. In the foreground is a plastic container with a sample bag inside (for added security). On the left is a 15-litre water drum used to carry water to areas where none was available.



Figure 4.4: Side view of the hydro jet in operation on a root mat surface.



Figure 4.5: View from behind the hydro jet in operation on a root mat surface.

#### Step 2 Pre-erosion photograph and preparation of the hydro jet

A digital photograph was taken before hydro jet erosion testing in order to allow for later visual analysis of surface organic material, surface roots and root mat. The hydro jet container was filled with water and pressurised.

The jet nozzle was reset to the same fixed jet position before each test.

#### Step 3 Use of hydro jet on bank

The sediment catcher was placed in an appropriate position on the bank area to be tested, whilst trying to minimise the disturbance to any surface root material present. The hydro jet was discharged at each site with the jet nozzle at a constant distance from the bank. Any material that was removed from the bank by this process, but not eroded by the jet, was carefully removed from the edge of the catcher and not retained.

#### **Step 4 Collection and post-erosion photograph**

Each sample was placed into an airtight bag and then positioned in a plastic container for transport to the laboratory. A post-erosion photograph was taken of the test site. Laboratory analysis as outlined below was then undertaken.

### 4. 4 Laboratory analysis

In the Environmental Research Institute of the Supervising Scientist (*eriss*) laboratory (Jabiru), samples were oven dried at a temperature of  $105^{\circ}$  C, weighed, passed through a 2 mm sieve and the coarse organics and gravels were removed by hand and weighed separately. The total weight of the material eroded using the hydro jet for each site was recorded.

The samples were transported back to the University of Wollongong laboratory and analysed using a laser grain size analyser (Malvern Mastersizer 2000). The size range measured by the Mastersizer is from clay through to coarse sand (2 mm is upper limit). Therefore, coarse organics and gravels were removed before being examined.

## **4.5 Effects of vegetation on flow**

Velocity measurements were taken adjacent to two distinctly different vegetation types and around a vegetated bar using an OSS-B1 impellor type current meter with a 100 mm fan diameter. For all velocity readings, if the depth was greater than 60 cm, readings were taken at 0.2, 0.4, 0.6, and 0.8 of the total depth. If less than 60 cm, one reading at 0.6 of the depth measured from the water surface was obtained.

Velocity profiles were constructed adjacent to a grassed bank at the upstream single-thread site and extended from the area where the vegetation was exhibiting an influence on the flow out into the channel. Vertical velocity profiles were taken as described above at 50 cm intervals from the bank into the channel until no bank influence was apparent.

Velocity profiles were also conducted adjacent to a tree-lined bank at the upstream anabranching site although a tree alcove proved to be more difficult to sample than the straight grass bank. Strong reverse currents occurred in the

downstream end of the alcove and the direction of the current meter had to be aligned directly into the flow in order to gauge the correct flow velocity. Measurements were taken at the downstream end, in the middle and at the upstream end of the alcove. Readings were taken as far as possible out into the flow.

The construction of velocity profiles around a single vegetated bar located at the single-thread site were taken at intervals along the length of the bar and extended out into the channel until the bar exerted no apparent influence. Velocities were measured from 2 metres upstream to 10 m downstream of the bar.

## **4.6 Velocity Cross-sections**

A velocity gauging cross-section was constructed across the single-thread site in the Dry season of 2001 by *eriss*. The suspended cable had 22 stations at 5 m intervals (110 m). Velocities were measured across the cable from the left bank to the right bank and back again (double traverse) using an OTT C-31 impellor type current meter for a variety of discharges. For both traverses, measurements were taken at each station for 0.2, 0.4, 0.6 and 0.8 of the total water depth (if deeper than 60cm) using a current meter suspended from a boat. Velocities were measured at a variety of discharges ranging from below bank full to over bank full (Figure 4.6).

## 4.7 Effects of fire on vegetation

The presence of fire scarring and the height above the base of the tree was examined for each mature tree along the vegetation cross-sections (measured along cross-sections and in channel). A significant fire occurred after the fieldwork had been completed and *eriss* (M.J. Saynor) obtained photographs of the study sites. The photographs were used in order to perform a qualitative analysis of the effects of burning on the channel.



Figure 4.6: Location of the 5 m intervals between sites along the suspended cable at the downstream single-thread reach. Note: flow is from right to left. The left bank is 15 metres behind photographer and right bank is in the distance (grass is visible on the right bank through gaps in the trees).

# **4.8 Statistical analyses**

A two-tailed t test was used to test for significant differences. The t test was used to assess the significance of changes in means between the erosion rates of hydro jet test samples. The t test was also used to determine whether the tree density, basal area and grain size values were significantly different.

# **4.9 Limitations**

Due to the rules and conditions set by Energy Resources Australia (ERA) for work on the Ranger Uranium Mine Lease, it was not possible to perform experimental modifications to the banks of the study area. Therefore, the removal of sections of root mat from the bank to confirm whether or not these were the stabilising factors on bank reinforcement was not permitted. In the absence of such regulations it would have been desirable to conduct a series of tests on a section of bank and change a number of parameters before each test such as the removal of surface root mat and the removal of the banks (and roots) back to the base of the tree. This would have enabled the determination of the extent to which a tree influences the bank away from its own trunk.

An experimental limitation was the low bank angles and whilst testing the root mat surfaces, it was difficult not to disturb the outside of the surface area being tested with the catcher. Care was taken on slightly disturbed sites to not use the jet around the outside edge of the test erosion area.

Due to the late onset of the Wet in the early part of the season, preliminary hydraulic erosion jet sprays were undertaken. This initial period was helpful, with the field refinement of experimental techniques.

Due to occupational dangers, such as crocodiles, it was too difficult and dangerous to conduct the hydraulic erosion jet tests during the latter part of the Wet. This process involves spraying the banks and the water levels during the late Wet prohibited the banks even being observed for approximately one month of this period. Therefore, the majority of this work was carried out during the Dry season.

# Chapter 5 Results

# **5.1 Introduction**

Quantitative vegetation data were obtained for the anabranching and singlethread reaches including detailed plan view maps, transverse vegetation transects over the channels and floodplain and tree density and basal area measurements made downstream along the bank tops.

The hydraulic erodibility of three different vegetated surface types was sampled using a hydro jet during the 2002 Dry season. Further analysis of the sedimentology and organic content of the samples was undertaken in the laboratory.

Flow velocity fields were measured adjacent to a tree-lined and a grass-lined bank, as well as a velocity field measured around a mid-channel vegetated bar. These detailed velocities were designed to complement stage-related cross-sectional velocity data undertaken at the single-thread reach (this study) and the anabranching reach (Roberts, 1991) for a range of discharges. In combination they enable an assessment of vegetation interactions with flow.

# 5.2 Vegetation mapping

Tree and shrub species were identified for the maps, cross-sections and tree densities, and a list of the species found within the study area is provided (Appendix 1).

Detailed vegetation maps were produced for the two main study sites. Figure 5.1 shows the within-channel and bank top tree species and also the position of LWD within the single-thread reach. For the single-thread reach, there were more trees growing within the channel and the composition of dominant tree species reflected that of a melaleuca forest.

Figure 5.2 illustrates the distribution of tree species lining the banks of all three channels and the within-channel vegetation and LWD of the upstream



Figure 5.1: Single-thread vegetation map. The bold lines represent the areas that are at or above bankfull level. The highlighted bar shows the location of the velocity profiles in Figures 5.20 and 5.21.



Figure 5.2: Anabranching study reach vegetation map. The bold lines represent the areas that are at or above bankfull level. The highlighted area in the left channel shows the location of the tree bank velocity profiles in Figure 5.18.

anabranching study reach. The anabranching reach had a higher density of trees lining the left and middle channels. The composition of dominant species reflected that of a monsoon riparian forest.

## **5.3 Vegetation transects**

Quantitative vegetation transects were surveyed across four sections of the study reach (Figures 5.3 and 5.4 illustrate the cross-section locations). These were located at the downstream single-thread study site (Figure 5.5), upstream anabranching study site (Figure 5.6), GS 009 - upstream single-thread (Figure 5.7) and the downstream anabranching site located between the upstream single-thread and downstream single-thread cross-sections (Figure 5.8). The key for the tree species and groundcover categories are shown in Figure 5.9. Transects were extended from the woodland on the left bank side, through the riparian forest zone and channel, to the woodland across the right floodplain. All mature species measured along each transect have been illustrated on the cross-section along with the cumulative base and breast height diameters per plot and the cumulative height of trees per plot. The ground cover and number of immature species contained in each plot have also been illustrated on the cross-sections.

The mean base and breast height diameters for the mature trees across each transect are shown in Table 5.1.

transects.

 Cross-section location
 Base diameter (cm)
 Breast height diameter (cm)
 Height (cm)

Table 5.1: Mean base and breast height diameters and mean heights across vegetation

Cross-section location	Base diameter (cm)	Breast height diameter (cm)	Height (m)
Downstream single-thread	17.54	12.22	4.69
Upstream anabranching	20.95	15.83	8.64
Upstream single-thread	7.87	5.93	2.24
Downstream anabranching	16.44	13.12	6.50



Figure 5.3: Location of the upstream anabranching and upstream single-thread vegetation transects (Photograph taken by M.J. Saynor).



Figure 5.4: Location of the downstream single-thread and downstream anabranching vegetation transects (Photograph taken by M.J. Saynor).



Figure 5.5 Downstream single thread vegetation transect



Figure 5.6 Upstream anabranching vegetation transect



Figure 5.7 Upstream single thread vegetation transect



Figure 5.8 Downstream anabranching vegetation transect



Figure 5.9 Key to the tree species and groundcover classes of the vegetation transects

### 5.4 Bank tree-densities

#### 5.4.1 Tree spacing

Tree density results for the two main study reaches show a difference in mature tree spacing along the banks of each site (see Table 5.2). The mean distance between trees lining the banks of the single-thread reach was significantly greater than the spacing of trees lining the banks of the anabranching channels (P < 0.05). In addition, there was a significant difference between the banks of the single-thread site. The density of trees along the left bank of the single-thread reach was significantly greater than the trees lining the right bank (P < 0.05), so not all differences relate to channel pattern. This may be an indication of the influence of fire on the right bank. The average distances between mature trees along the banks of the three channels of the anabranching reach were tested for significantly different to the density of trees lining the banks of the middle channel. Both the left and middle channels had significantly higher tree densities than the right channel (P < 0.05).

#### 5.4.2 Basal area coverage

The basal area coverage of trees was calculated for the bank top vegetation at the downstream single-thread and upstream anabranching study reaches (Table 5.2). The basal area coverage of mature trees was not significantly different between the anabranching and the single-thread banks. This was most likely attributable to the large degree of variance in the anabranching base diameters as a result of the mixture of fully mature and immature trees.

For the downstream single-thread reach, the left bank had a basal area coverage value of 2514.9cm<sup>2</sup>/100m<sup>2</sup> for mature trees and the right bank coverage was 1345.3cm<sup>2</sup>/100m<sup>2</sup>. These were also not statistically significant different.

The upstream anabranching reach had a large range of basal area coverage values. The values for the banks of these channels are shown in Table 5.3. The left channel was not significantly different to the middle channel or the right channel. The middle and the right channel coverage values were significantly different (P < 0.05).
		Mean		
		Tree	<u>Number</u>	Basal area
		spacing	of trees/	$(cm^{2}/100m^{2})$
Channel type	Location	<b>(m)</b>	$100 \text{ m}^2$	
Single	Left bank	5.18	3.73	2514.9
Single	Right bank	7.14	1.96	1345.3
Anabranching	Left bank of left channel	3.92	6.51	8919.8
Anabranching	Right bank of left channel	2.46	16.53	19515.4
Anabranching	Left bank of middle channel	2.4	17.36	21298.1
Anabranching	Island between middle and right channel*	3.77	7.04	3899.2
Anabranching	Right bank of right channel	4.91	4.15	1257.8

Table 5.2: Tree densities and basal area coverage for the banks of the upstream anabranching study reach and downstream single-thread study reach.

\* The small island separating the middle and right channels was very narrow and the tree density measurements had to be taken down the centre of the island. Therefore, these values were used as the right bank of the middle channel and the left bank of the right channel.

Clearly, the single channel banks have lower basal area coverage values and fewer trees per  $100 \text{ m}^2$  than the anabranching banks, the exception being the low values along the right anabranch that over recent years has been severely fire affected.

## **5.4.3 Dominant species**

The composition of dominant species along the upstream anabranching channel banks was different to those for the downstream single-thread banks (see Table 5.3). The table shows the dominant species along the banks of both sites in the following categories: number of trees per  $100m^2$ , basal area, absolute frequency and importance value rank. The absolute frequency is the number of times a species was counted in at least one of the quadrats around a sample point. Therefore, if a tree was measured at 5 out of 5 sample points, its absolute frequency would be 100 %. The importance value ranking, gives the most dominant species for a site in terms of a combination of relative density, relative dominant species for that sample location to be identified. For the anabranching reach, in terms of basal area coverage, number of trees per 100 m<sup>2</sup> and absolute frequency, the left bank of the left branch was dominated by *Lophopetalum arnhemicum*. The next most dominant species was *Corymbia porrecta*.

The right bank of the left branch was also dominated by *Lophopetalum* arnhemicum with a value of 14365.2 cm<sup>2</sup>/100 m<sup>2</sup>, 73 % of the basal area coverage for this bank. The same species was also the most dominant species for the left bank of the middle channel. *Syzygium forte ssp. potamophilum* and *Carralia brachiata* were the next two most dominant species for both the right bank of the left channel and left bank of the middle channel.

The island between the middle and right channels had a total of 9 tree species and the right bank of the right branch had 8. *Corymbia porrecta* was clearly the most dominant species for both of these banks.

The large diversity of species measured on the island between the middle and right channels and on the right bank of the right channel (9 and 8 species respectively) is probably a reflection of the level of disturbance as a result of fire and related flood damage in the more open vegetation.

Melaleucas dominated both of the banks at the single-thread site (Table 5.4). *Melaleuca argentea* was the dominant species along the left bank for basal area coverage, but on the importance value rank, the *Melaleuca viridiflora* was three times as dominant as *Melaleuca leucadendra*. The right bank was dominated by *Melaleuca viridiflora* in all categories.

				<b>Importance</b>
Location	Number of trees	$\frac{\text{Basal area}}{(2)^{2}}$	Absolute	value
	per 100m <sup>-</sup>	(cm <sup>-</sup> /100m <sup>-</sup> )	Frequency	rank
Left bank - single	M. viridiflora	M. argentea	M. viridiflora	M. viridiflora
		М.		
Right bank - single	M. viridiflora	viridiflora	M. viridiflora	M. viridiflora
		L.		L.
LB - Left channel	L. arnhemicum	arnhemicum	L. arnhemicum	arnhemicum
		L.		L.
RB – Left channel	L. arnhemicum	arnhemicum	L. arnhemicum	arnhemicum
		L.	L. arnhemicum and S. forte	L.
LB - Middle channel	L. arnhemicum	arnhemicum	ssp. potamophilum	arnhemicum
Middle of small				
island	A. lacertensis	C. porrecta	A. lacertensis	C. porrecta
RB - Right channel	A. latescens	C. porrecta	A. latescens	C. porrecta

Table 5.3: Dominant species of single-thread and anabranching banks.

M = Melaleuca, L = Lophopetalum, S = Syzygium, A = Acacia and C = Corymbia

# 5.5 Hydraulic erosion jet

## 5.5.1 Dry Season

The hydro jet tests of bank strength from the Dry season in 2002 are shown in Figure 5.10. The three main surfaces were tree-lined banks, grass-lined banks and the root mat at the base of within channel trees, mainly melaleucas.

Densely tree-lined banks were located in the left and middle channels of the well-defined anabranching reach. Hydro jet tests were performed on sections of bank that were located near the base of the dominant species within the reach (*Lophopetalum arnhemicum* and *Syzygium forte ssp. potamophilum*). The average amount of material eroded from this bank surface was 144 grams (4.8 grams/second) (Figure 5.10). Figures 5.11A and B show a detailed view of a tree-lined bank, before and after spraying.

Grass-lined banks were common within the single-thread reach, but only areas of almost pure grasses on the bank were chosen as test locations. The average amount of material eroded from the grass-lined banks was 227 grams (7.56 grams/second) (Figure 5.10). Figures 5.11C and D show a photograph of before and after testing of a grass site.

The third erosion surface tested was a root mat at the base of within-channel trees, which mainly consisted of melaleucas. The average amount of material eroded from the root mat was 43 grams (1.44 grams/second) (Figure 5.10). The location of the root mat at the head of a vegetated bar, and a view of a test surface post-erosion test, are shown in Figures 5.2E and F.

The relationships between erosion rates and grain size for the test surfaces are plotted as regression equations in Figures 5.12 (tree-lined), 5.13 (grass-lined) and 5.14 (root mat). It can be seen that there is no apparent relationship between grain size and erosion rate for the tree-lined and the root mat surfaces. However, the grass-lined test surfaces do appear to show a weak correlation between erosion rate and grain size. With increasing sand percentage in the sample, the erosion rate increased and consequently with increasing silt and clay percentage in the sample the erosion rate decreased.

The amount of material eroded using the hydraulic erosion jet from tree-lined banks was statistically significantly greater than the amount eroded from the root mat surfaces (t = 4.75, D.F. = 14, P< 0.05). The amount eroded from tree-lined banks was

not statistically significantly less than grass-lined banks, however the difference did approach significance (t = 2.05, D.F = 14, P< 0.10). The amount of material eroded from the grass-lined and root mat test surfaces were significantly different (t = 5.18, D.F. = 14, P< 0.05).

An analysis of variance on the pooled means was unable to be performed because this procedure can only be used when the largest sample standard deviation is no more than twice as large as the smallest (Moore, 1995) (see Appendix 2).



Figure 5.10: Hydraulic erosion jet measurements with averages fitted to each surface (Mean: Grass-lined = 227grams, Tree-lined = 144grams and Root mat = 43grams).



Figure 5.11A and B: Before and after erosion testing a tree-lined bank.



Figure 5.11C and D: Before and after erosion testing a grass-lined bank.



Figure 5.11E and F: Location of root mat tests at the head of bar (left) and after a root mat erosion test (right).

**Tree-lined bank** 



Figure 5.12: Sedimentology and erosion rate for tree-lined surfaces.

Grass-lined bank



Figure 5.13: Sedimentology and erosion rate for grass-lined surfaces.

Root mat



Figure 5.14: Sedimentology and erosion rate for root mat test surfaces.

## 5.5.2 Grain size

A grain size analysis was conducted on each of the hydro-jet erosion samples (shown in Table 5.4) using a laser grain size analyser (Malvern Mastersizer 2000). A statistical analysis, using t-tests, of the sand, silt and clay percentages in the samples showed that for all three surfaces the grain size percentages were statistically significantly different. The sand percentages contained in the samples from root mat surfaces were significantly greater than for both tree-lined and grass-lined banks (P< 0.05). In turn, the percentage of sand in the grass samples was significantly greater than for tree-lined samples (P< 0.05).

The silt and clay percentages contained in the tree-lined bank surfaces were significantly greater than both the grass-lined and root mat test surfaces (P< 0.05). Additional analysis revealed that the percentage of silt and clay in the grass-lined samples was significantly greater than for the root mat samples (P< 0.05).

A one-way analysis of variance on the pooled means was also unable to be performed on the above results because the largest grain size sample standard deviations were more than twice as large as the smallest grain size sample deviations for all samples (Moore, 1995).

Surface	Sorting	Average	Mean %		
		grain size	Sand	Silt	Clay
Tree	Poorly Sorted	Fine Sand	84.21%	14.29%	1.50%
Grass	Moderately Well Sorted	Medium Sand	93.64%	6.08%	0.27%
Root mat	Moderately Well Sorted	Medium Sand	98.07%	1.88%	0.04%

Table 5.4: Grain size data from hydro jet testing samples.

## 5.5.3 Bank slope

The average slope measurements taken on the surfaces tested with the hydro jet showed that tree-lined banks had an average bank angle of  $60-65^{\circ}$ , grass-lined  $50-55^{\circ}$  and root mat surfaces had an average slope of  $55-60^{\circ}$  (see Appendix 3).

# **5.6 Flow velocities**

The velocity measurements around a tree root bank, grassy bank and a root mat bar, show the influence of the different vegetation types on flow velocity, flow resistance and potential bank erosion. The grass-lined bank velocity profiles (velocity Figures 5.15 and 5.16 and plan view Figure 5.17) show that the grasses exhibit a retarding influence on the near-bank flow conditions. Flow entered the grass as eddies and the velocities near the grass bank were recorded as pulses. The eddies were then dissipated as they travelled through the grass. This process would presumably change with an increase in flow depth, as the grasses would probably lie down in the flow direction.

Velocity measurements from the tree-formed alcove showed the water in the downstream end of the alcove was moving in an upstream direction, thereby creating negative velocities (see velocity Figures 5.18 A, B and C and plan view Figures 5.19 A and B). As the measurements were extended out into the channel, the velocities orientated to a downstream direction. The near bank velocity at the upstream end of the alcove was very much higher than that near the grassy bank. These high velocities are generally true of the tree-lined banks of the anabranching reach. However, velocities near the bank within the alcove were extremely low and had virtually no erosive potential at this near bankfull discharge (~  $30 \text{ m}^3 \text{ s}^{-1}$ ).

Velocities around the treed bar, protected by the trees root mat at the upstream end, showed that the mature clump of (5) melaleucas growing at the head of the bar, had a substantial effect on flow around the obstruction (see velocity Figures 5.20 A, B, C, D and E). Furthermore, hydraulic resistance was high in the lee of the melaleucas and at the tail of the bar, which was densely populated with grass. Up to 2 metres from the centre point of the narrow bar tail, velocities were still measurably lower than in a similar position upstream.

Another interesting result was recorded downstream of the bar. Ten metres downstream of the velocity profile across the tail of the bar (Figure 5.20 D) velocities

were still significantly influenced. Further deposition could occur within this zone, especially under falling stage conditions. The presence of the bar shifted the thalweg further to the right away from the bar.

The plan view diagram (Figure 5.21) shows the velocity change around the bar. The mean velocity of each vertical profile was taken and the distribution of flow around the bar shows that it is the melaleucas at the head of the bar that are causing a significant amount of hydraulic disturbance. Figure 5.22 illustrates an example of deposition in the lee of a similar vegetated bar.

The velocity gradients adjacent to the three vegetated surfaces were calculated in order to show the areas of greatest velocity change near the bank. The velocity gradient was steepest adjacent to the tree-lined bank ( $0.8 \text{ m s}^{-1}/\text{m}$ ). The head of the root mat bar had the second highest velocity gradient ( $0.65 \text{ m s}^{-1}/\text{m}$ ) and the grass-lined banks had the lowest velocity gradient ( $0.45 \text{ m s}^{-1}/\text{m}$ ). These results show that the tree-lined banks are subject to the highest amount of velocity shear and the grasses the lowest.

## 5.7 Channel velocity cross-sections

Velocity cross-sections were gauged across the entire channel at the singlethread site at discharges of: 2.5, 6, 39, 42, 52, 97, 123 and 150 m<sup>3</sup> s<sup>-1</sup>. A discharge of approximately  $40m^3$  s<sup>-1</sup> is bankfull. Figure 5.23 shows a comparison of the in-channel change in velocities as flow height increases at the three upstream anabranching channels and at the downstream single-thread cross section. It can be seen that as flow exceeds bankfull, the in-channel flow at the upstream anabranching site begins to slow down whereas the single-thread velocities continue to increase. This is almost certainly due to *momentum transfer* as flow enters the dense vegetation lining the anabranching channels before re-entering the channel and slowing the within-channel velocities.



Figure 5.15: Grass velocity profile 1. Velocities are shown in m  $s^{-1}$ .



Figure 5.16: Grass velocity profile 2. This was located downstream of

Single channel	Velocity profiles extending from grass bank into channel	Flow
Grass-lined bank		

profile 1. Velocities are shown in m s<sup>-1</sup>.





Figures 5.18 A, B and C: Velocity measurements adjacent to a tree-lined bank. 'A' is in the upstream end, 'C' the downstream. Velocities are shown in m s<sup>-1</sup>.



Figure 5.19 A: View of the tree-formed erosional alcove for which velocity measurements were made. The blue line indicates the movement of flow within the alcove. The velocity profiles are shown in Figure 5.18 B and C.



Figure 5.19 B: Location of velocity profiles adjacent to tree-formed alcove. The velocity profiles are shown in Figure 5.18 A and B.



Figures 5.20 A, B and C: Bar velocity profiles heading in a downstream direction.





Figures 5.20 D and E: The top profile is across the tail of the bar and the bottom one is downstream of the top profile 10 m.



Figure 5.21: Plan view distribution of mean velocities around bar. The dashed lines represent the proposed velocity. The horizontal lines represent the velocity profiles shown in Figure 5.20.



Figure 5.22: Looking upstream along a similar bar to the one sampled for velocity, showing the lee side deposition.



Figure 5.23: Relationship between discharge and in-channel velocities for the upstream anabranching and downstream single-thread sites (Jansen and Nanson, in prep)

Floodplain velocities were measured during an overbank flow at the downstream singlethread cross-section at a discharge of  $123 \text{ m}^3 \text{ s}^{-1}$  (see Figure 5.24). On the right floodplain of the downstream single-thread reach, where melaleuca forest exists, the velocities were lower than in the shallower and less vegetated right-hand extent of the floodplain. In an area between the right bank and the woodland, where there is a discontinuous sandy overbank channel, velocity was 0.43 m s<sup>-1</sup> compared to 0.196, 0.261 and 0.253 m s<sup>-1</sup> in the vegetated areas. There was also a significant flow velocity measured 15 metres away from the left bank at the end of the cable. At this point, velocity was higher out of the channel with a value of 0.424 m s<sup>-1</sup>. Therefore, as flow escapes the confines of the channel, the velocities are often very closely tied to those in the channel.

Floodplain and island velocities were also measured for an overbank flow at the upstream anabranching reach for a discharge of  $110 \text{ m}^3 \text{ s}^{-1}$ . The results are shown in Figure 5.25. There was a relationship between the flow velocities and the roughness induced by the vegetation, with the lowest velocities in the areas of dense vegetation.

# 5.8 Effects of fire

Across each of the 4 vegetation transects, fire scarring was measured both in terms of its presence or absence and height from the base for each mature tree. This was performed in order to gauge the significance of fire as a formative process on the development of channel pattern. The average height of fire scars across the 4 vegetation cross-sections showed the recent measurable effects of fire. The downstream single-thread reach had an average height of fire scar per tree of 158.15 cm (31% of plots contained fire scars), upstream anabranching reach 78.47 cm (22% contained fire scars), upstream single-thread site 46.15 cm (15% of plots with fire scars) and the downstream anabranching site 169.42 cm (35% of plots contained trees with fire scars). The presence and height of fire scars can be used to determine the level of fire activity and its importance for each study reach. Transects and trees with a large amount of fire scars, then there has never been a fire in that area or there has been a substantial period of time elapse since the last fire. Figures 5.26, 5.27 and 5.28 show the effects of a fire that burnt an extensive area of the right floodplain

within the study area, during the 2002 Dry season. At the upstream anabranching and single-thread sites, the fire was observed to have burnt across the right floodplain down to the channel banks.



Figure 5.24: Downstream single-thread velocities at a discharge of 123 m<sup>3</sup> s<sup>-1</sup>



Figure 5.25: Upstream anabranching cross-section velocities at a discharge of 110 m<sup>3</sup>s<sup>-1</sup>



Figure 5.26: Right floodplain of the downstream single-thread site after fire. (Photograph taken by M. Saynor).



Figure 5.27: Right bank of the right channel and right floodplain of the upstream anabranching site. (Photograph taken by M. Saynor).



Figure 5.28: Fire has burnt across the right floodplain to the right bank of the upstream single-thread site during Dry season of 2002 (Photograph taken by M. Saynor).

# Chapter 6 Discussion and Conclusion

# **6.1 Introduction**

This thesis has examined vegetation distribution, bank erodibility and flow velocity differences between single-thread and anabranching reaches along an anabranching section of Magela Creek. There are some significant differences between the two types of channel planform. The vegetation of the single-thread reaches is a Melaleuca forest, with low tree densities on the bank and vegetation growing within the channel. The predominantly grassy banks are less stable and the root mat at the base of the within channel trees is highly resistant to erosion. Flow is moderately retarded near grass banks at low discharges, but decreases with increasing discharge and velocity. Flow velocity was particularly high near the head of the rootmat covered bars and velocity gradients were steep and decreased with distance along the bar.

The anabranching site was dominated by thick monsoonal vegetation, which was effective at stabilising the banks. The measured bank erodibility along these reaches was higher than for the root mat, but the dense lining of trees and large roots was successful at protecting the banks from erosion. Reverse currents was measured in a tree-formed erosional alcove. Such alcoves act to dissipate the erosional energy of the flow. In the anabranching reach during overbank flow, velocities are actually lower than during within bank flows, probably because of significant momentum transfer resulting from the drag effect of island and floodplain vegetation.

# **6.2 Vegetation patterns**

## **6.2.1 Single-thread reaches**

The single-thread reaches are characterised by a low density of mature trees along the banks, large amount of grass on banks and a high proportion of mature trees growing within the channel. The single-thread reach was composed of tree species including *Melaleuca argentea*, *M. leucadendra* and *M. viridiflora* that were growing both within the channel and along the banks. Tree densities along the banks of the downstream single-thread reach were significantly lower than the upstream anabranching reach (section 5.4.1) and had smaller basal areas by comparison with the anabranching reach. The banks were lined with fewer trees and more grass; the vegetation here is less hydraulically rough due to wide tree spacing and also smaller basal areas. As a consequence the trees are less effective at stabilising the banks, because they do not substantially reduce flow and erosion, nor do they provide significant bank strength through root reinforcement. This site also had a large number of trees (mainly melaleucas) growing within the channel (see Figure 5.1). These trees can be considered as 'colonisers' and readily occupy low competition areas. The effects of the trees growing within the channel and their low densities on the banks will be dealt with further in a later section on flow hydraulics.

The dominance of melaleucas at the single-thread site appears to be linked to the levels of disturbance for this reach. A natural stimulus such as fire, flood or drought among the *Myrtacaeae* commonly causes widespread germination of seeds (Woodall, 1982, 1983). The adaptation of melaleucas to flood, fire, sediment erosion and deposition, falling water tables during establishment, prolonged inundation and periods of water logging, has benefited the three species of melaleuca significantly in areas where the levels of disturbance are high. In fact, they appear to thrive in such settings. Should there be continued aggradation within the Magela Creek system, and deposition of contemporary sediment onto the much older marginal alluvium (Nanson *et al.*, 1993), the habitat available to melaleucas will further expand (Williams, 1984).

Grasses, such as *Sorghum*, are common at the single-thread reaches and are effective at binding and protecting the surface sediments of banks and bars from erosion. The grasses played an important role in binding the surface sediments with their roots, but they also enhanced secondary deposition from bed-load movement during large floods on the bar and bank surfaces. They are the most fire tolerant of all the vegetation types along Magela Creek and act to stabilise alluvium after fire has removed the trees.

Grasses colonise considerably large areas of the single-thread reach and they provide an effective form of surficial drag resistance and top soil surface binding, but as discharge and stage height increase, the grasses lay in a downstream direction with the flow (see Figure 6.1) and become less effective at influencing flow and they begin to control bed-load movement and enhance deposition with bed-load particles

deposited in the lee of the grass. This process operates both within the channel on bar surfaces (see Figure 6.1) and also on the banks, which are frequently overtopped each Wet season with approximately 12 bankfull flows per year. The frequent nature of burning reduces the grass cover by almost 100% in the single-thread reaches and the grass has to grow again at the beginning of the following Wet season. The inference being that in the initial period of flow at the beginning of the next Wet season, the bar and bank surfaces are likely to experience significant erosion due to decreased vegetation cover. However, this is only likely to occur if the Wet season rains start early and grasses do not yet protect large areas, something that rarely occurs. The "build up" usually precedes the Wet season when convectional storms produce rains that establish a grass cover early in the season.



Figure 6.1: Grasses lying down with the flow (foreground) and trees in background still influencing flow.

The upstream single-thread transect was found to have the lowest crosssectional tree densities for the four vegetation transects (Figure 5.7 and see Figure 5.5 for the next lowest). The single-thread sites are located downstream of the anabranching reaches in areas where the channels converge into a single channel for a short distance (Figures 5.3 and 5.4).

#### 6.2.2 Anabranching reaches

The anabranching reaches are characterised by a high-density tree lining of the banks and islands and very few grasses. The dominant trees lining the banks of the anabranching reach, such as Lophopetalum arnhemicum, were rarely found growing within the channel unless aided by an obstruction. Monsoonal species such as this appear to have a deep root system that do not spread away from the trunk as effectively as the trees that grow readily within the channel. These species are more successful at growing in areas where a seed can be trapped and the sappling protected in a moist and shaded area whilst a juvenile. These species are not colonisers, but are 'consolidators'. That is, they appear to grow on surfaces that are already stable and then further increase the stability through thick growth and large tree size. This appears to be a function of seed dispersal, reliance on a moist location for germination and a deep root system. Seeds are dropped from mature trees during the periods of flow in the Creek and transported by the flow. L. arnhemicum is commonly associated with monsoon forest near permanent water in deep sandy soils (Brock, 2001). The position of backflow billabongs within the reach (see Figure 5.3) may play a significant role in the initial growth and regeneration of this species following disturbance. It is the moisture and fire protection provided by the billabongs that act as refuges that appears to contribute in the re-establishment post-disturbance of this species, as will be discussed in a later section. The thick vegetation and the stability of the channel banks and islands appear to be interrelated, with the vegetation facilitating the increase in bank stability that provides suitable sites for germination. At the downstream anabranching site thickets of L. arnhemicum were found growing on the channel and island banks adjacent to the backflow billabong at this location. Therefore, given an appropriate period of low disturbance (~ 5 years), the L. arnhemicum and other species that inhabit consolidated surfaces, such as Syzygium forte ssp. potamophilum and Carralia brachiata, are able to establish and begin to substantially increase the stability of a site. Once fully established these species would be able to tolerate low intensity ground cover fires, but not large fires that spread through the canopy (Kym Brennan, personal communication, 2002).

The downstream anabranching site had less dense vegetation located on the main island by comparison with the upstream anabranching study reach. It is probable that a large fire destroyed the pre-existing vegetation, as evidenced by a significant number of immature species (including *L. arnhemicum*) and cover of grasses both on the island surface and along the banks. The density of vegetation at the islands channel banks is the important factor for channel stability. The anabranching reaches both show higher vegetation densities in close proximity to the channel. Conversely, the single-thread channels do not. The channel boundary is the most important area for channel and lateral stability. Substantial modifications to the channel boundary resulting from significant fire, flood damage or other disturbance can affect the lateral stability within these systems and thus influences their ability to form anabranching channel pattern.

## 6.2.3 Floodplains

The floodplains beyond the channels of the four transects are characterised by tall and mid-storey grass, relatively few large mature trees in open areas on the left bank and a dense band of *M. viridiflora* on the right floodplain. Extending from the upstream single-thread site to the downstream single-thread site, there are a large number of melaleucas (*M. viridiflora*) located on the right floodplain. This species is commonly found in moister areas around seasonal watercourses and is found in moist depressions within the study reach and also grows along the banks (Brock, 2001). The floodplains of the four vegetation transects do not appear to show any marked variation in the composition of species. Some of the other species found on the floodplains of the four transects include *Pandanus aquaticus*, *P. spiralis* and *Barringtonia accutangula*. These species will also grow near the channel and the frequent overbank flows per year may contribute to their growth in the moister areas of the floodplain.

The right floodplain of the upstream anabranching site contained fewer *M*. *viridiflora* (see Figure 5.6) than the other three transects. The floodplain at this site was considerably more open and contained species such as *Corymbia porrecta* and *Eucalyptus tetrodonta*. The right channel of this site had aggraded to a higher level than the other two channels and this may have increased the level of the water table in the right floodplain. A number of mature trees (mainly *C. porrecta*) showed signs of crown die back, that may be due to a rising water table.

#### 6.2.4 Summary of vegetation

The dominant tree species of the downstream single-thread study reach were melaleucas, with *M. viridiflora* being particularly dominant along the banks (Table 5.3 and Figure 5.1) and on the right bank floodplain (Figure 5.5). The other two melaleucas, *M. argentea* and *M. leucadendra*, were predominantly found growing within the channel.

The melaleucas appear to be dominant due to the high levels of disturbance within the single-thread reach. This area seems to be operating within a state of dynamic change due to floods and fires preventing the vegetation of the area from stabilising. The dominant grass species here is *Sorghum* sp.'s located within the channel, on the banks and across the floodplains. The grasses, although frequently burnt, are readily able to re-establish at the beginning of each Wet season

The upstream anabranching reach shows a marked difference in dominant species between the banks of the island and the banks of the right channel (Table 5.3). The banks of the large island and the left bank of the left channel are dominated by monsoonal riparian forest tree species (*L. arnhemicum* and *S. forte ssp. potamophilium*), which are related to the closed canopy, moisture of the site and the fire protection from the billabongs. These features then become self-propagating and are able to regenerate large quantities of further consolidating monsoonal species, and these in turn are able to stabilise, and increase the flow resistance.

The banks of the right channel show a high degree of species diversity and a marked increase in grasses. This appears to be a function of several large fires over preceding years and in 2002. Bendix and Hupp (2000) found that species diversity might be maximised at high, rather than intermediate, levels of disturbance.

The vegetation of the downstream anabranching site appears to contain a mixture of the vegetation from the other anabranching site and the downstream single-thread site. Why? It is most likely that this site is in an intermediate phase of recovery following a significant disturbance due to a large fire. On the left bank of the left channel and at the beginning of the right floodplain (see Figure 5.8), two mature *Syzygium suborbiculare* trees were found. These species are mostly found in open forest or woodland (Brock, 2001), but the left bank site is approaching a closed canopy forest. Therefore, the site may have undergone substantial transformation since the establishment of these individuals, an assumption that the site was originally open woodland, but has been disturbed by fire.

## 6.3 Bank erosion

The hydro jet device was used to quantify the erodibility of three differently vegetated surfaces within the study area. The tree-lined banks were chosen as test locations because they were representative of the anabranching reaches. Tree densities were almost twice as high at the upstream anabranching reach compared to the downstream single-thread site and trees were the most dominant vegetation type on the banks. Grass covered banks were chosen to represent the banks of the upstream and downstream single-thread sites, as grass was more dominant than trees on these banks. Root mat located at the head of within-channel trees was also tested, as the resistance of this surface to erosion was believed to be one of the factors allowing trees to grow within the channel and form bars.

A significant difference in erodibility was not measured between the tree-lined and grass-lined banks (Section 5.5.1). However, although no significant difference was found, a difference is believed to exist (Figure 5.10). The high variance in the results from the grass-lined hydro jet tests prevented the statistical comparison with tree-lined banks from achieving a significant difference. The large degree of variance in the grass-lined tests was attributed to the diversity of areas colonised by grasses. Site selection was based on the dominant vegetation type of grass and not the bank sedimentology. Several sites tested with the hydro jet were grass-lined banks growing on essentially fresh sandy deposits, with other tests located on sections of stable bank material, which were not recently deposited. The depositional nature of the site colonised by grass was thus determined to influence the erosion rate. The regression lines fitted to the sedimentology and erosion rate (Figure 5.13) indicate that there is a difference in the erodibility of these surfaces in relation to grain size. Erosion rate relationship appears to be positively correlated to sand content, and with increasing silt and clay content the erosion rate decreases. Other things being equal (bank material), it is believed that grass banks are more vulnerable to erosion than the welltreed banks. Grass is not as effective at binding the surface sediments, which leads to a higher amount of particle detachment from the surface beneath the impinging hydro jet.

Many of the tree-lined banks contained few roots exposed at the surface, but a considerable amount of roots were believed to extend from the channel further into the bank. As discussed in the limitations (Section 4.9), direct modifications to the

bank surface were unable to be made. The tree-lined banks were the steepest and most well defined of the test sites. There was a lower density of root mat located at the bank surface and the root distribution was substantially different to that of the melaleucas. The root mat of the melaleucas was very dense, whereas the root mat of the monsoon species was more open, but still effective. It is not the root mat that appears to be especially important within the anabranching reaches. The large amount of protection provided by the densely spaced projecting roots and tree trunks are probably substantial components of the erosion resistance. Furthermore, the grain sizes of the tree-lined banks contain a significantly larger amount of silt and clay by comparison with the other two (Section 5.5.2). However, even though the sedimentology was different to the other sites, this was not found to influence the erosion rate measured with the hydro jet. In the natural setting the higher silt and clay in the tree-lined banks may increase resistance to erosion, such as found by Schumm (1960), even though the results here do not reflect this. The sediments of the anabranching (tree-lined) tests had a median grain size of fine sand and silt percentage was significantly higher than for the other two test surface sediments ( $\sim 20\%$ ). Therefore, sedimentology may also be playing a minor role in stabilising the banks of the well-defined anabranching channels.

The resistance of the root mat surfaces to particle detachment by comparison with the grass and tree-lined banks illustrates one of the factors enabling melaleucas to grow within the channel. Resistance of the fine surface root structure to hydro jet erosion, combined with the high tolerance of the within-channel species to flood and fire disturbance, make them ideally suited to their niche within the system. The largely surficial root mat was resistant to erosion, but once the jet breached the dense layer of roots, the next layer of sediment was relatively easily removed. Melaleucas also have a network of larger roots that spread quite close to the surface both upstream and downstream, providing anchorage to readily mobilised substrate. The root mat protects the surface from significant erosion and the main root system provides anchorage. Abernethy and Rutherfurd (2000, 2001) found that *Melaleuca ericifolia* had a low depth spreading root system. The exposed roots of melaleucas within the study reach do appear to have a root system that spread laterally, quite widely from the base.

The root mat samples contained a high percentage of sand (see Table 5.4) and thus no relationship was found between erosion rate and a change in dominant grain size.

It has been demonstrated here that the bank lining vegetation of the anabranching reach is able to exert an influence over the channel geometry by substantially reinforcing and altering the near bank area. By comparison, the vegetation on the banks of the downstream single-thread reach is unable to substantially influence the bank strength.

Huang and Nanson (1998) determined that the influence of bank strength was greater on channel width than on the depth or cross-sectional area of the channel. They also found that although bank strength due to bank vegetation, might increase by an order of magnitude or more, its influence on the geometry of the river channel is not so proportionate. In fact, bank strength appears to have a relatively limited impact compared to flow discharge, and as a consequence, the common bivariate relations between flow discharge and hydraulic geometry are widely applicable.

The three different vegetation types have been shown here to vary in their response to particle detachment beneath an eroding jet. The hydro jet was designed to provide a transportable, reproducible, standard uniform procedure for testing the surface erodibility of three different vegetation types. The results show that the root mat at the base of within-channel trees provides a substantial amount of erosion resistance. As a result, the melaleucas are able to grow within the channel. The grasslined banks are the least effective vegetation type in terms of binding of the substrate. Therefore, grasses can readily colonise active sandy features, but their influence on bank strength is low and they need to be succeeded by a more stabilising type of vegetation, in order to substantially increase the stability of a site. The tree-lined banks are not as highly resistant to erosion as are the root mats. This was interesting considering the obvious stability of the tree-lined banks of the multi-channel reaches. The stability is due in part to the protruding tree roots protecting the sediments from high shear stress, but the dense lining of trees and the large roots and trunks may also provide a greater amount of support for these very steep banks at flow.

## **<u>6.4 Flow velocities</u>**

Widely spaced trees, small shrubs and grasses, such as found at the singlethread sites, are effective at reducing bank shear at low velocities, but their effectiveness decreases with increasing velocity, especially if they are flexible. Comparatively, the anabranching reach contains large, dense, mature, woody trees that are effective at reducing shear up to very high velocities, as they are inflexible. However, they may cause local scour upstream and alongside their trunks if they are widely spaced as velocity increases around the obstruction. This effect may be reduced as a consequence of dense tree spacing, but for in-channel trees the effect may be amplified. The detailed results of the velocity distributions adjacent to the tree and grass banks and around the vegetated bar is now discussed.

The velocity distribution within a tree-formed erosional alcove was measured in the left channel of the anabranching reach (see Figure 5.2). The formation of treelined erosional alcoves is a unique situation and may result from the bank being eroded between existing mature bank top trees, or it could also be an area where a tree has fallen into the channel. The operation of a reverse current at such a low discharge (below bankfull ~  $30 \text{ m}^3 \text{ s}^{-1}$ ) (Figure 5.18 B and C) suggests that the reverse current is buffering the erosive energy of the flow. The flow enters the alcove at the downstream end (Figure 5.19 A), slows significantly as it travels upstream and reenters the flow at a considerably lower velocity than it entered. This form of momentum transfer, slows the flow around similar features within the channel and reduces the erosive nature of the flow. The velocities at the upstream end of the alcove (Figure 5.18 A) are more representative of the near-bank flows along sections of channel where alcoves are absent within the multi-thread reach. The change in velocities away from the erosional alcove was highest for the tree-lined bank. This demonstrates the substantial resistance to erosion by high shear velocities. The normally steep-sided banks in the anabranching reach are subject to considerable bank shear and rely on their protective tree trunk and root system to withstand such high erosional forces. In that sense the protruding banks and trees in the anabranching reach take the brunt of the erosional forces, leaving the alcoves to generate large eddies that interact with the downstream flow, inducing considerable drag overall.

The velocity measurements extending from the grass-lined bank (Figure 5.15, 5.16 and 5.17) into the flow show the grassy banks to be subject to relatively low

shear stresses. The change in velocities near to the grass bank was substantially lower than the other two surfaces. At the flow height measured (just below bank full), the grasses were observed to absorb pulses of flow energy that entered the grass and were dissipated as they travelled through the grasses. Grasses appear to play a role in enhancing fine material deposition and exhibit a moderate influence on flow in the channel. This process probably only occurs up to a flow above which the grasses lay in a downstream direction. They play a role in binding and protecting the soil and trapping bed material, especially in the single-thread sites.

The root mat at the head of the within-channel bars has been demonstrated to make the bank sediment significantly more resistant to erosion than is the sediment on the tree-lined and grass-lined banks. Vegetation grows within the channel and affects the flow hydraulics of the single-thread sites, especially by deflecting flow onto the banks. It is considerably difficult for trees to establish along the banks of these reaches because deflection of flow around trees growing within the channel impacts on and erodes banks. The bed roughness of within-channel vegetation (trees) is able to override bank vegetation in determining the channel geometry (Huang and Nanson, 1997). Therefore, the single-thread banks are exhibiting a complex hydraulic response to within-channel vegetation. The existence of the within-channel vegetation considerably influences the role of bank vegetation and is able to override the bank vegetation in determining the channel geometry, causing widening.

The depth of the flow and the position of the clump of melaleuca trees at the head of the bar studied (Figure 5.1) were determined to be important variables governing the effect of such a vegetated bar on flow hydraulics. The right bank side of the bar was deeper and a considerable amount of the flow was concentrated along this side. The left side of the bar was shallower and velocities and flow depths were lower down this side. The velocity gradient was steepest at velocity profile B (Figure 5.20). The change in the velocity gradient adjacent to the root mat was lower than for the tree-lined banks, but still indicates the substantial resistance to erosion of these surfaces. This profile was extended adjacent to the melaleucas at the head of the bar where the root mat acted as a significant reinforcement. A zone exists where lower velocities were measured in the lee of the vegetated bar (Figure 5.20 E), an area likely to experience deposition under falling stage conditions (Figure 5.22). As a consequence grass and immature vegetation colonises such areas and may be the nucleus for downstream bar growth. Bar growth may lead to upstream or downstream
amalgamation with other bars and this may lead to island growth. A simple, 3-stage model of bar growth has been devised for Magela Creek. Step 1 involves the initiation of seedling growth in the channel (Figure 6.2 and 6.3). Step 2 is the beginning of the sediment deposition in the lee of the obstruction that is beginning to influence downstream flow (Figure 6.4). Step 3 shows that, depending on the position of the tree within the flow; the bar may join with other bars and form a complex bar. This can support grass and several different mature and immature tree species as well as the original mature tree(s) (Figure 6.5).



Figures 6.2 and 6.3: These photographs show Step 1: the growth of immature tree species in the bed of the channel. During this immature stage, scour can occur upstream and beside the obstruction.



Figure 6.5: Step – 3 Amalgamation and species diversification and successional change. The dashed lines show the outline of the initial bars.

This model of bar formation is based on considerable qualitative field evidence. It integrates the various processes observed operating within the reach and relates them to proposed bar growth. Tooth and Nanson's (2000) 3-phase model of bar, island and ridge formation could also be applicable to the study area and deserves to be investigated.

It would appear as though the landforms within the single-thread reaches are possibly evolving, but aerial photograph evidence from the 1950's to the present, suggests that the downstream single-thread site has remained essentially unchanged over this period, so the rate must be very slow.

Therefore, in areas such as the single-thread reach where there are a significant number of vegetated bars, the vegetation growing in the channel is probably hindering the development of the vegetation on the banks. The growth of bars near the banks deflects the flow into the bank and causes a less stable channel system. There are no significant bar formations in the highly stable anabranching reach.

#### **6.4.1 Floodplain velocities**

Vegetation on the floodplain also reduces velocities, but the type and density of floodplain vegetation differs. Grasses and small shrubs play an important role when flow is just above bankfull. As the water level continues to rise, these vegetation types have less effect on the hydraulic roughness because they are flexible and bend to reduce their resistance. Consequently, velocities on the floodplain can rise to values similar to those in the channel. The dominant tree species on the floodplain is *Melaleuca viridiflora* and this species has a long, straight and relatively narrow trunk, which is less effective at increasing roughness. The velocities on the right floodplain of the upstream anabranching site (Figure 5.25). This shows that the effect of vegetation on the floodplain velocities is similar between the two different channel types. It has been shown that the floodplain velocities of the anabranching and single-thread reaches are comparable due to the similar vegetation composition of the floodplain.

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#### **<u>6.4.2 Stage and velocity relationship</u>**

An interesting relationship was found between velocity variation and an increase in stage height between the upstream anabranching and the downstream single-thread sites over bankfull. The anabranching channels show a marked decline in velocities as stage height increases (Figure 5.23). Conversely, the downstream single-thread site does not display such a decrease in velocity with increasing stage height (Figure 5.23). It is proposed that the decrease in velocities with increasing stage height in the anabranching channels is a result of the roughness of the thick vegetation. As flow enters the vegetation the velocity is substantially decreased along the channel margins (Figure 5.25). Once flow leaves the thick monsoonal vegetation and re-enters the channel, momentum transfer occurs when slowing floodplain and island water mixes with faster water in the channel.

Comparatively, the single-thread site contains less dense vegetation on the banks and there are no densely vegetated islands. As stage height increases, the velocities in the channel also increase because there is relatively little drag induced from the vegetation (Figure 5.23).

### 6.5 Role of fire

The position of backflow billabongs within the reach may play a significant role in the initial growth and regeneration of monsoon species on the channel islands and on the floodplain following disturbance. Figure 6.6 shows a possible situation where the vegetation of the large island has been destroyed following a large fire. The combination of the backflow billabong and the seeds dispersed from significant pockets of monsoon species along the escarpment may lead to a reasonably short time span for post-fire recovery. Figure 6.7 shows the possible second phase of recovery. Substantial vegetative recovery may establish adjacent to the moisture provided by the billabong and vegetation successional changes lead to the maturity and density of trees increasing significantly. Figure 6.8 shows the climax monsoon vegetation on the large islands. Thick monsoonal vegetation increases the stability of an island through its influence over bank strength and hydrology. These areas then remain virtually unburnable over long time periods.



Figure 6.6: Stage 1 - post-fire. A backflow billabong located adjacent to a large island within the study area. This diagram shows the possible effects of a large fire, with all vegetation destroyed on the large island and adjacent areas.



6.7: Oblique aerial of downstream anabranching site. The highlighted area shows the regeneration of species adjacent to the semi-permanent water in the backflow billabong. The lack of mature trees on the upstream end of the island and the thick regeneration in the highlighted area is believed to be the result of a large fire (Photograph taken by M. Saynor).



Figure 6.8: Well-vegetated, stable, large island with fully established monsoonal vegetation (Photograph taken by M. Saynor).

As described in Section 6.2.3, a significant number of the dominant trees (for example *C. porrecta*) on the right bank of the right channel at the upstream anabranching site are showing crown die back and some are of poor health. The combined effects of the 2002 Dry season fire and trees that are stressed or unhealthy may be the nucleus for channel avulsion because the channel-floodplain resistance to erosion is substantially lowered. A splay is forming on the eroding bank of the right channel of this burnt area and Smith *et al.* (1989) have shown that splays could potentially indicate the initiation of a channel avulsion. A splay forming on the top of a levee could lead to bank incision and subsequently a new channel could avulse out across the floodplain. It has been shown that both avulsion and accretion may be formative processes of island development within Magela Creek. Fire appears to be the main process that would substantially lower the level bank resistance provided by the riparian vegetation, in order to trigger a channel avulsion.

### 6.6 Conclusion

Riparian vegetation along the lowland anabranching channels of Magela Creek plays an important role in influencing bank strength, flow hydraulics, sediment erosion and deposition, and bar and island formation. This study has demonstrated that the occurrence of anabranching and single-thread channels is related to differences in vegetation composition, bank erodibility and flow characteristics.

Well-defined anabranching reaches are characterised by a high density of monsoon-forest species growing along the banks and on the islands. The dense vegetation lines the narrow and deep channels and mature tree trunks and thick roots reinforce the banks. The forest is self-propagating and numerous juvenile species further increase sediment deposition and surface stability, especially if growing in dense thickets. The islands appear to be resistant to penetration by fire.

The single-thread reaches are characterised by generally low-density melaleuca forest with numerous trees growing within the channel, low bank tree densities and grass-lined banks. The trees growing within the channel form multiple bars and small islands and the single-thread reaches are consequently wider and shallower than the anabranching reaches.

Bank hydraulic erodibility was measured using a quantitative hydro jet instrument specifically designed for this purpose. The most resistant vegetated surface was the root mat located at the head of bars. The next most resistant was the tree-lined banks of the anabranching reach. The grasses on the banks of the single-thread reaches were the most easily eroded of the three surfaces.

Velocity fields were measured close to the tree-lined and grass-lined banks and also around a vegetated bar. The velocities near the banks of the anabranching reach show that they are able to withstand very high bank shear. The heads of the bars were also considerably well adapted to resisting flow concentration around their root base. The grasses were the least effective of the three vegetation types at resisting bank shear. The tree-formed alcove exhibited in the anabranching reach was generating upstream flowing eddies that, along with the retarding influence of the dense vegetation during overbank flows, was able to lower the in-channel velocities and thus reduce erosion. As flow height increases in the anabranching reaches, the inchannel velocities decrease due to substantial drag and consequent momentum transfer associated with the dense monsoonal islands. A similar velocity reversal does not occur in the less densely vegetated single-thread reaches.

Riparian vegetation, bank erodibility and flow hydraulics clearly influence the occurrence of channel pattern within the lowland anabranching section of Magela Creek. The stable anabranching reaches contain dense monsoonal vegetation that is highly effective at protecting banks from erosion and reducing flow velocities through momentum transfer. The single-thread melaleuca forest reaches are bar-dominated, with highly resistant root mat at the base of within-channel trees. These reaches are less effective at reducing flow velocities and thus erosion and deposition are ongoing within these unstable environments.

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# Appendices

# Appendix 1

Species	Family
Acacia aulacocarpa	Mimosaceae
Acacia auriculiformis	Mimosaceae
Acacia difficilis	Mimosaceae
Acacia holosericea	Mimosaceae
Acacia lacertensis	Mimosaceae
Acacia latescens	Mimosaceae
Acacia mimula	Mimosaceae
Antidesma ghesaembilla	Euphorbiaceae
Asteromyrtus symphyocarpa	Myrtaceae
Banksia dentata	Proteaceae
Barringtonia acutangula	Lecythidaceae
Buchanania obovata	Anacardiaceae
Carallia brachiata	Rhizophoraceae
Corymbia alba	Myrtaceae
Corymbia porrecta	Myrtaceae
Erythrophleum chlorostachys	Caesalpiniaceae
Eucalyptus papuana	Myrtaceae
Eucalyptus ptychocarpa	Myrtaceae
Eucalyptus tetrodonta	Myrtaceae
Grevillea pteridifolia	Proteaceae
Jacksonia dilatata	Fabaceae
Livistona benthamii	Arecaceae
Lophopetalum arnhemicum	Celastraceae
Lophostemon grandiflorus ssp. riparius	Myrtaceae
Lophostemon lactifluus	Myrtaceae
Maranthes corymbosa	Chrysobalanaceae
Melaleuca argentea	Myrtaceae
Melaleuca leucadendra	Myrtaceae
Melaleuca viridiflora	Myrtaceae
Pandanus aquaticus	Pandanaceae
Pandanus spiralis	Pandanaceae
Phyllanthus reticulatus	Euphorbiaceae
Planchonia careya	Lecythidaceae
Santalum lanceolatum	Santalaceae
Syzygium forte ssp. potamophilum	Myrtaceae
Syzygium suborbiculare	Myrtaceae
Tabernaemontana orientalis	Apocynaceae
Xanthostemon paradoxus	Myrtaceae

### Appendix 2

Sample	Root mat (x	(-mean)2	Grass	(x-mean )2	Tree	(x-mean)2
1	24.38	, 357.97	45.57	32876.94	164.61	<b>427.25</b>
2	10.78	1057.56	331.5	10936.98	94.73	2421.62
3	51.38	65.29	99.95	16113.76	106.57	1396.52
4	43.59	0.08	210.7	263.74	41.46	10502.15
5	22.38	437.65	492.5	70532.74	236.66	8597
6	34.18	83.17	108.7	13980.7	37.26	11380.62
7	41.09	4.88	152.3	5568.14	242.25	9664.86
8	61.88	345.22	293	4366.57	35.65	11726.72
9	21.86	459.67	253	680.69	189.16	2044.85
10	23.05	410.06	302.8	5759.29	73.26	4995.68
11	38.98	18.66	453.5	51343.03	164.86	437.65
12	94.08	2578.61	305.7	6207.86	141.29	7.02
13	42.68	0.38	122	11006.11	281.98	19055.04
14	76.29	1088.34	153.5	5389.03	141.1	8.07
15	63.38	403.21	78.98	21877.37	208.33	4146.07
Total	649.98	7310.75	3403	256902.95	2159.2	86811.1
Mean	43.3		226.9		143.94	
Variance	522.2		18350		6200.8	
Standard deviation	22.85		135.5		78.75	
Minimum	10.78		45.57		35.65	
Maximum	94.08		492.5	~ [	281.98	

_	Grass		Grass		Grass _	
Grass - lined	Sand %	(x-mean)2	Silt %	(x-mean )2	Clay_%°	(xmean)2
1	90.22	11.7	9.35	10.69	0.43	0.03
2	92.99	0.4225	6.86	0.61	0.14	0.02
3	94.69	1.1	5.31	0.59	0	0.07
4	96.04	5.76	3.9	4.75	0.06	0.04
5	97.91	18.23	2.09	15.92	0	0.07
6	100	40.44	0	36.97	0	0.07
7	100	40.44	0	36.97	0	0.07
8	95.76	4.49	4.2	3.53	0.04	0.05
9	94	0.13	5.86	0.05	0.14	0.02
10	95.55	3.65	4.25	3.35	0.2	0.005
11	96.08	5.95	3.77	5.34	0.14	0.02
12	95.92	5.2	4.08	4	0	0.07
13	82.25	129.73	16.63	111.3	1.12	0.72
14	87.54	37.21	11.67	31.25	0.79	0.27
15	85.65	83.84	13.35	52.85	1.01	0.55
Total	N/A	368.29	NIA	318.17	NIA	2.075
Mean	93.64%		6.08%		0.27%	
Variance	26.31		22.73		0.15	
Standard deviation	5.13		4.77		0.38	
Minimum	82.25		0		0	
Maximum	100		16.63		1.12	

	Tree		Tree		Tree	
Tree - lined	Sand %	(x-mean)2	Silt %	_	Clay %	(x-mean)2
				(x-mean)2	-	
1	79.43	22.85	17.9	13.03	2.67	1.37
2	82.74	2.16	15.27	0.96	1.99	0.24
3	83.39	0.67	15.21	0.85	1.4	0.01
4	86.45	5.02	12.57	2.96	0.98	0.27
5	76.4	61	20.7	41.09	2.9	1.96
6	83.14	1.14	15.5	1.46	1.36	0.02
7	94.85	113.21	5.02	85.93	0.13	1.88
8	91.21	49	8.47	33.87	0.33	1.37
9	81.08	9.8	16.65	5.57	2.27	0.591
10	78.15	36.72	19.84	30.8	2.01	0.261
11	87.09	8.29	11.42	8.24	1.48	0.0004
12	85.51	1.69	13.49	0.64	1	0.25
13	78.05	37.95	19.54	27.56	2.4	0.81
14	86.4	4.8	12.63	2.76	0.98	0.27
15	89.24	25.3	10.12	17.39	0.64	0.74
Total	NIA	379.6	N/A	273.11	NIA	10.04
Mean	84.21 %		#####		1.50%	
Variance	27.11		19.51		0.72	
Standard deviation	5.21		4.42		0.85	]
Minimum	76.4		5.02		0.13	]
Maximum	94.85		20.7		2.67	]

	Root mat	_	Root m	at	Root mat	
Root mat	Sand %	(x-mmean)2	Silt %	x-mean)2	Clay %	_
				_	-	(x-mean)2
1	98.09	0.0004	1.91	0.0009	0	0.0016
2	100	3.72	0	3.53	0	0.0016
3	93.72	18.92	5.95	16.56	0.33	0.08
4	97.6	0.22	2.4	.0.27	0	0.0016
5	100	3.72	0	3.53	0	0.0016
6	99.26	1.42	0.74	1.3	0	0.0016
7	100	3.72	0	3.53	0	0.0016',
8	93.85	17.81	5.97	16.73	0.17	0.017
9	100	3.72	0	3.53	0	0.0016
10	96.59	2.19	3.41	2.34	0	0.0016
11	93.93	17.14	5.92	16.32	0.15	0.012
12	100	3.72	0	3.53	0	0.0016
13	100	3.72	0	3.53	0	0.0016
14	98.03	0.002	1.97	0.008	0	0.0016
15	100	3.72	0	3.53	0	0.0016
Total	N/A	83.74	N/A	78.24	N/A	0.1282
Mean	98.07%		1.88%		0.04%	
Variance	5.98		5.59		0.009	
Standard deviation	2.45		2.36		0.096	
Minimum	93.72		0		0	
Maximum	100		5.97	J	0.33	

### Appendix 3

Site	Slope	Orientation	Vegetation type	Eroded weight (g)
1	45-50	Head bar (upstream)	Root mat	24.38
2	60-65	Head bar (u/s)	Root mat	10.78
3	50-55	Head bar (u/s)	Root mat	51.38
	70-75	Head bar (u/s)	Root mat	43.59
5	45-50	Head bar (u/s)	Root mat	22.38
6	60-65	Head bar (u/s)	Root mat	34.18
. 7	55-60	Head bar (u/s)	Root mat	41.09
. 8	60-65	Head bar (u/s)	Root mat	61.88
9	55-60	Head bar (u/s)	Root mat	21,86
- 10	45-50	Head bar (u/s)	Root mat	23.05
11	45-50	Head bar (u/s)	Root mat	38.98
12	45-50	Head bar (u/s)	Root mat	94.08
13	50-55	Head bar (u/s)	Root mat	42.68
14	55-60	Head bar (u/s)	Root mat	76.29
15	60-65	Head bar (u/s)	Root mat	63.38
			Mean	43.3

Site	Slope	Orientation	Types of veg	Eroded Weight (g)
1	45-50	flow aligned	Grass	45.57
2	45-50	flow aligned in bend	Grass	331.47
3	45-50	flow aligned	Grass	99.95
4	65-70	flow aligned 15-20 u/s	Grass	210.65
5	45-50	flow aligned 15-20 d/s	Grass	492.47
6	75-80	flow aligned bioturbated	Grass	108.65
- 7	45-50	flow aligned	Grass	152.27
8	45-50	flow aligned	Grass	292.97
. 9	50-55	alow aligned	Grass	252.98
10	45-50	flow aligned	Grass	302.78
11	45-50	flow aligned	Grass	453.48
12	55-60	flow aligned	Grass	305.68
13	45-50	flow aligned	Grass	121.98
14	50-55	flow aligned	Grass	153.48
15	45-50	flow aligned	Grass	78.98
			Mean	226.9

Site	Slope	Orientation	Types of Veg	Eroded weight (g)
1	65-70	flow aligned	Trees, moss	164.61
2	65-70	flow aligned	Trees, moss	94.73
3	55-60	upstream 30	Trees	106.57
4	60-65	upstream 45	Trees	• 41.46
5	60-65	flow aligned	Trees	236.66
6	65-70	flow aligned	Trees	37.26
7	50-55	flow aligned	Trees	242.25
8	50-55	upstream 40	Trees	35.65
9	60-65	downstream	Trees	189.16
10	80-85	downstream	Trees	73.26
11	60-65	upstream	Trees	164.86
12	55-60	flow aligned	Trees	141.29
13	60-65	downstream	Trees	281.98
14	60-65	* downstream	Trees	141.1
15	70-75	flow aligned	Trees	208.33
			Mean	143.9