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RATES AND CONTROLS OF STREAMBANK RETREAT AND EROSION IN THREE TROPICAL STREAMS IN NORTH-EASTERN QUEENSLAND

Thesis submitted by

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for the degree of Doctor of Philosophy
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ABSTRACT

Streambank retreat is a natural fluvial process altered by a variety of direct and indirect human activities that is controlled by interactions between a range of hydrological, geomorphological and vegetative factors. These may include climate, discharge, bed slope, bank material and stratigraphy, bank height, bank angle, curvature and the various attributes of bank vegetation. There has been considerable progress in our understanding of these processes and their interactions in temperate regions, but our knowledge of bank retreat in tropical streams is relatively poor. Few quantitative studies of bank retreat or erosion are published for the tropics. In particular, there is a paucity of data on vegetation characteristics, their interaction with retreat-causing variables and their contribution to bank retreat or erosion. This thesis addresses these issues by investigating the response of 34 sites in three north-eastern Queensland streams (2 wet tropics, 1 wet-dry tropics) to the 2003/2004 wet season, observing rates and types of bank retreat and the suite of driving forces that were responsible for this retreat.

Variations exist in streambank retreat rate between climatological regions. Banks of streams in tropical environments tend to retreat at greater rates because they experience greater specific stream power, more frequent bankfull events and higher annual flows than streams in other regions. Global trends also exist between bank retreat and stream width and drainage area. However, no global trends appear to exist between bank retreat relative to channel size and stream width. Modelling retreat of the study banks against climatological regime showed that they retreated at equivalent rates to streams of similar size elsewhere but at lower rates than streams from similar climatological regimes. These comparisons are only valid as far as datasets of differing quality and quantity allow. Analysis of 2003/2004 wet season hydrology suggested that these low rates could be partly attributed to the high recurrence possibility of the wet season.

Variations in streambank retreat rate also exist within climatological regimes. The largely heterogeneous nature of streams and associated variability of dominant erosion driving forces is responsible for this variation. This study did not identify any direct relationship between streambank retreat and any measured variable. However, thresholds existed with regard to specific stream power (> 130 W m^{-2}), curvature (< 2.0), bank height (> 3.2 m) and bank angle (> 45º), which explained the variability of bank retreat rates. Bank retreat was low until these thresholds were passed. When these thresholds were exceeded, retreat rates were more variable, with the steep banks retreating faster than more gradually sloped banks. There was no

direct relationship between root area ratio (RAR) at any point on the bank and bank retreat. However, an exponential decay relationship existed between RAR at depths of 3 m and maximum bank angle: banks occupied by dense basal root networks were less steep, indicating an indirect relationship between bank retreat and basal RAR.

Variations in erosion at different depths down a bank can ultimately control overall bank retreat. Thus, variations in local factors and their control of erosion are as important to measure as retreat itself. Specifically, the variations in RARs and their interactions with other local factors, such as depth or sediment characteristics are a major control of scour rates. Erosion rate variability in the study streams decreased logarithmically with both increasing RAR and gravel content of the bank. Thus, those banks with denser root networks and greater coarse fragment content were less likely to erode. The absence of erosion of gravel-dominated strata in this study is anomalous, but may be partly attributed to the low magnitude and short duration of the flows of the 2003/2004 wet season.

Riparian influence on bank erosion and retreat is largely attributed to its effect on bank sediment strength and cohesion, but its influence on flow redirection away from the bank is also important. Root densities play a major part in these processes – greater densities provide increased cohesion, improved armouring of the bank from primary and secondary flows and sediment aggregation due to the input of organic matter. Root densities generally vary according to above-ground vegetation characteristics, sediment characteristics (moisture, texture, gravel content) and depth. There were linear relationships between root density (using RAR as the measure) and tree density that declined in strength with increasing depth at the 34 study banks. RARs at shallow depths were shown to be highly variable where trees were tall. RAR also varied greatly with depth. Wet tropics banks showed marked drops in RAR at depths of 2.5-3.0 m. A similarly significant decline was evident in wet-dry tropics banks at 2.0 m. No significant relationship existed between sediment and RAR.

This thesis has highlighted the multi-faceted and complex nature of bank erosion and retreat in tropical Queensland streams, as reported in the literature for many temperate systems and the few tropical systems that have been studied. It suggests that specific stream power, curvature, bank geometry, RAR and gravel content and the interaction between these variables are all important in understanding bank erosion and retreat. But despite the extremes of the climate in the study region, erosion responses to a flood of moderate magnitude were within the range expected from other studies, suggesting, albeit with a small dataset, an adaptation of these systems to regular flooding. A larger dataset, including data on their reaction to events of larger magnitude may alter this relationship. It is clear that knowledge of these fluvial processes and characteristics in association with an appreciation of other local and catchment-based processes is essential for the development of appropriate catchment-wide and reach-based management plans.

CONTENTS

FIGURES

TABLES

CHAPTER 1
STREAMBANK STABILITY: TROPICAL STREAMS IN A GLOBAL CONTEXT

1.1 Introduction

This thesis focuses on streambank stability in north-eastern Queensland coastal streams in both wet and seasonally-dry (wet-dry) tropical regions. Erosion and/or aggradation of the streambank face and lateral shifts in the position of the bank top were the principal streambank traits examined to assess stability, with the influence of various geotechnical, geometric and biological parameters on the behaviour of these traits examined in detail. Particular attention was given to stratigraphic and vegetative influences on streambank behaviour in both regions. There are few quantitative data on streambank stability, especially on vegetative influences on stability, in the north-eastern Queensland region. This thesis begins to address this shortcoming. The context of this study is provided in Section 1.5, which reviews the extent of information on streambank retreat and its main driving forces and identifies the specific information gaps which this study addresses.

1.2 Terminology

Confusion over terminology in the field of streambank stability complicates comparisons between studies. Streambank erosion and stream migration are commonly used terms and refer to similar interrelated processes. Streambank erosion contributes to the migration of streams and to floodplain formation through direct removal of material by flowing water or the slipping of bank material into the stream after weakening (Couper and Maddock 2001, Lawler *et al.* 1997a). Stream migration is the lateral movement of a stream resulting from bank erosion, avulsion and meander cut-off. Migration resulting from bank erosion only occurs if there is deposition of sediment on the inner bank in conjunction with erosion of the outer bank, otherwise channel widening occurs. While bank erosion and stream migration refer to separate processes, they are obviously linked. However, discussions of these processes are often complicated by inconsistent terminology, requiring that definitions be established here. Different terms used to describe bank erosion include bank retreat (Dapporto *et al.* 2003), scour (Hickin and Nanson 1984), failure and various types of failure, such as rotational slumping (Abernethy 1999), depending on active processes; while terminology for migration varies similarly. In this study, ‘scour’ and ‘fluvial entrainment’ will be used interchangeably to describe the direct removal of sediment from the bank face by streamflow. The term 'mass failure' and its various subclasses will be used accordingly (Section 3.2.2). 'Erosion' will also be used as a general descriptor of shifts in position of the bank face. 'Channel/stream migration' will be used to describe whole channel movement across the floodplain, while 'bank retreat' or 'bank advance', which are types of migration, will be used to describe lateral shifts in the position of the bank top.

This study involved field measurements in streams of two tropical regions of northern Australia, termed the 'wet tropics', characterised by high rainfall (mean > 1500 mm a^{-1}) with considerable variation spatially and between and within years, and the 'wet-dry tropics', characterised by lower rainfall (mean = 640 – 1510 mm a^{-1}) with much higher spatial, inter-annual and intra-annual variability (Kapitzke *et al.* 1996, Kapitzke *et al.* 1998, McDonald and Weston 2004) (Section 2.1 and 2.2). The hydrology in these two regions reflects the rainfall characteristics and thus offers the opportunity to explore streambank dynamics under two different process regimes.

1.3 Streambank stability: components

Streambank erosion and retreat are natural phenomena, but can be complicated by the interaction with human catchment use. The human use of floodplains and riparian lands has impacted upon the relative significance of the factors that determine erosion and retreat rates, creating conflict between utilitarian and natural stream values (Couper and Maddock 2001). Bank erosion and retreat, especially human-influenced, are thus central themes in stream and land management.

Streambank erosion and retreat are influenced by a number of factors that can act either exclusively or in concert, such as stream and catchment size, stream power, curvature, bank sediment, bank height, vegetation and slope. Variability in the driving forces of bank erosion is well reported: Mosley (1975) and Pizzuto and Meckelnburg (1989), for example, discuss the large variety of factors that determine erosion rates, while many authors (e.g. Abernethy and Rutherfurd 1998, Hudson and Kesel 2000, Larsen and Greco 2002 and Yarbrough 2000) discuss particular influential characteristics.

Erosion occurs when thresholds with respect to one or more of the erosion driving forces are exceeded. These thresholds are often breached as a result of the natural variability of the flow regime of the stream and the channel adjustments to these variations (Summerfield 1991). Events with higher stream power, for instance, are more likely to exceed the thresholds of boundary conditions required to cause erosion, while gradual deposition of larger sediment particles on point bars results in redirection of flow and possible exceedence of velocity and pressure thresholds on the outside bank. This response is enhanced by human land and stream uses, which may increase the magnitude of processes or reduce threshold levels beyond which geomorphic work is performed, effectively making it easier for changes to occur (Couper and Maddock 2001).

1.4 Contribution of vegetation to erosion control

At a broad scale, stream reaches bordered by riparian vegetation can be up to 150% less erodible than those bordered by agriculture (Micheli *et al.* 2004) and the removal of riparian vegetation can be associated with unstable stream stretches (Rowntree and Dollar 1999). On a finer scale, the roots of all vegetation contribute to mechanical bank reinforcement (Abernethy and Rutherfurd 2001), bank buttressing (Thorne 1990), bank drainage and water uptake (Sperry *et al.* 1998, Stone and Kalisz 1991), flow resistance (Darby 1999) and soil aggregation (Miller and Jastrow 1990), all of which improve bank stability.

Mechanical binding of the bank sediments by roots improves bank stability and reduces the potential for direct scour. Increased root distribution and tensile strength provide the bank face with an extra cohesion that strengthens the bank material and improves bank stability (Abernethy 1999, Simon and Collison 2002). Similarly, bank buttressing effects provided by vegetation improves bank stability by protecting the toe and directly supporting bank material upslope. Release of binding agents by roots encourages sediment aggregation (Gyssels and Poesen 2003) and results in better structured and stronger bank sediment, while flow diversion provided by exposed roots moves erosive currents away from the bank face and reduces scour (Thorne 1990).

Both root density and tensile strength of the roots in the bank are important factors influencing the capacity of roots to strengthen streambanks, but root density is more significant (Abernethy 1999). Root area ratio (RAR) is an indicator of root density. While the effects of RAR on bank stability have been widely discussed (e.g. Abernethy and Rutherfurd 2000a, 2001, Simon and Collison 2002, Thorne 1990), its impact on fluvial entrainment has received less attention. It is clear that increased RAR provides a protective role against scour – for example, Dunaway e*t al.* (1994) described alluvial streambank erosion protection offered by the roots of herbaceous plant communities, noting a negative correlation between root density and erosion. However, their study was largely based *ex situ* in flumes and focussed on vegetation with mainly fibrous root matter. The present study examined streambanks vegetated often by complex riparian communities with heterogeneous root sizes and other characteristics. Few other examples of research on community root contribution to fluvial entrainment control exist (e.g. Swanson *et al.* 1982, Zimmerman *et al.* 1967).

1.5 Worldwide and Australian bank retreat rates: a review

Hooke (1980) and Lawler (1993a) provide rare earlier reviews of streambank retreat and erosion from a global perspective. This section builds on these reviews to provide a broad assessment of worldwide bank retreat rates. Variability in bank retreat rates and possible causes are discussed in the global context before the bank retreat rates of Australian and, specifically, northern Queensland streams are examined.

1.5.1 Streambank retreat rates: geographic variation

The rate at which streambanks retreat has both natural and anthropogenic implications. Bank retreat rates affect natural stream hydrology, sediment load and aquatic and terrestrial habitats, while also encroaching on environmental, political, social and economic values of surrounding land. Human uses of streams also encroach upon the natural stream values. Thus, there has long been interest in bank retreat and stream migration, as indicated by references in the late 19^{th} Century and early 20^{th} Century (e.g. Allen 1895, Dryer and Davis 1911, Lokhtin 1897), the mid-20^{th} Century (e.g. Dunford and Fletcher 1947, Goldthwaite 1937, Wolman and Leopold 1957) and more recently (e.g. Brizga and Finlayson 1990, Gilvear *et al.* 2000, Hickin and Nanson 1984). Much research has been undertaken in the developed and highly populated United States and other developed regions (e.g. Brice 1977, Leopold 1973), while only a few examples exist in tropical regions (e.g. Kale and Hire 2004, Salo *et al.* 1986) (Table 1.1).

Table 1.1 – Tally of bank retreat rate and erosion studies for different regions, resulting from a review of the relevant literature.

Review included literature from 1900 to the present and used GeoRef, GeoBase, Current Contents, Article First and Google Scholar.

Region	Number of Studies
USA	41
UK	27
Canada	12
Australia	11
Continental Europe	10
North Asia-Russia	5
Africa	3
Indian Subcontinent	3
South-East Asia	2
South America	1

More than 100 published studies of bank retreat exist (Table 1.1) but many are descriptive and few report rates especially at annual or event scales. Furthermore, many of the studies that discuss rates of retreat do not provide comparisons with previous studies performed in similar climatological, geomorphological, hydrological or sedimentological regimes. For example, Brice (1974) provided useful diagrams showing the retreat of his study channels and a discussion on meander evolution and development but directed little discussion towards actual rates of retreat in his or comparable studies.

1.5.2 Differences between climatological regions

Table 1.2 lists 115 published studies that report more than 160 separate retreat rates. Stream width is used as an indicator of stream size and is used to remove the effect of scale on bank retreat rates. Other factors that may affect retreat rates, such as stream type and drainage area, are not identified as this information is inconsistently reported; and many studies fail to state the width of the channel.

A simple analysis of the data in Table 1.2 shows that bank retreat rates vary considerably between climatological and associated hydrological regimes (Figure 1.1). Analysis of published data by ANOVA (and associated *post hoc* Tukey's tests) showed no significant differences between streambank retreat rates in cool temperate/sub-arctic and temperate studies, but significantly higher rates existed in tropical regions than in other climatological regions. ANOVA of width-standardised retreat data provided similar results. Comparable analyses by Gilvear *et al.* (2000), Guy (1981), Rutherfurd and Bishop (1996), and Salo *et al.* (1986) suggested similar patterns. Thus, climate and associated hydrology are important general predictors of bank retreat rate, but high variance in the data indicates that the influence of local factors is also important. This analysis emphasises the need to expand our knowledge of bank retreat of tropical streams and to establish tropical-based paradigms that remove the need for uncritical acceptance of theories established elsewhere.

Table 1.2 – Streambank retreat rates reported in the literature.

Note that level of location detail varies according to the scale of each study and/or the level of site detail given in each study.

Climate	Country	Location	Bank Retreat Rate ($m\ a^{-1}$)	Width (m)	Retreat as a % of Width	Source
Sub-arctic	Russia	Upper Ob R, Siberia	0 – 15	Large	–	Kulemina (1973)
Cool Temperate	Canada	North Nashwaaksis Stream	0 – ~2.0	–	–	Bray (1987)
	"	Pembina River, Alberta	3.35	64	5.25	Crickmay (1960)
	"	"	0.3	64	0.47	"
	"	Ontario (study stream unknown)	0.053 – 0.18	–	–	Dickinson and Scott (1979)
	"	Beatton River, British Columbia	0.475	370	0.13	Hickin and Nanson (1975)
	"	Various streams, British Columbia/ Alberta	0.73 – 9.41	30-281	1.9 – 9.9	Hickin and Nanson (1984)
	"	Rouge River, Quebec	~1.0 – 2.5	–	–	Lapointe and Carson (1986)
	"	Various streams, British Columbia	0.5	–	–	Nanson (1980)
	"	Beatton River, British Columbia	0.3 – 0.7	–	–	Nanson and Beach (1977)
	"	"	>1.0 – <7.0	–	–	Nanson and Hickin (1983)
	"	Little Smokey River	0.57	37	1.54	Nanson and Hickin (1986)
	"	Milk River	1.68	48	3.50	"
	"	Belly River	1.18	40	2.95	"
	"	West Prairie River	0.86	30	2.87	"
	"	Beaver River	1.41	52	2.71	"
	"	Waterton	3.93	70	5.61	"
	"	U. Eagle River	1.34	49	2.73	"
	"	L. Eagle River	0.71	50	1.42	"
	"	Swan River	1.52	46	3.30	"
	"	U. Shuswap River	1.73	63	2.75	"
	"	Pembina River	2.60	79	3.29	"
	"	Muskwa River	2.65	49	5.41	"
	"	Oldman River	7.26	93	7.81	"
	"	L. Shuswap River	1.89	92	2.05	"
	"	Chinchaga River	1.03	90	1.14	"
	"	Prophet River	2.34	140	1.67	"
	"	Sikanni Chief River	2.92	127	2.30	"
	"	Ft. Nelson River	4.44	278	1.60	"

Table 1.2 – continued.

Climate	Country	Location	Bank Retreat Rate ($m\ a^{-1}$)	Width (m)	Retreat as a % of Width	Source
Cool temperate	Canada	Mackenzie River, NWT	1.0	–	–	Smith and Hwang (1973)
	"	Ottawa River, Ottawa	0.35	–	–	Williams *et al.* (1979)
	Denmark	Various streams	0.0062	3.3	0.19	Laubel *et al.* (2003)
	"	Gjern Stream, Jutland	0.006	1.3	0.46	Laubel *et al.* (1999)
	"	"	0.013	1.7	0.76	"
	"	"	0.026	3.0	0.87	"
	"	"	0.008	4.7	0.17	"
	Hungary	Hernad River	5 – 10	50-60	10 – 16.67	Laczay (1977)
	Luxembourg	Schrondweilerbaach catchment	0.02 – 0.035	–	–	Duijsings (1987)
	"	"	~0.02 – 0.035	–	–	Duysings (1986)
	"	Birbaach catchment	0.008	–	–	Imeson and Jungerius (1974)
	Poland	Wisloka Valley	8.0 – 11.0	–	–	Klimek (1974)
	"	Dunajec River	0.4 – 1.0	30-120	0.83 – 1.33	Klimek and Trafas (1972)
	Sweden	Klaralven River	1.6	120	1.33	Sundborg (1956)
	"	"	0.23	"	0.19	"
	"	"	0.32	"	0.27	"
	Russia	Bol'shoi Egorlyk River	3.0 – 30	–	–	Karasev (1964)
	"	Unknown	2.25 – 3.1	–	–	Kondrat'yev (1968)
	"	"	100 (max)	–	–	Kondrat'yev and Popov (1967)
	"	"	10 – 15	–	–	"
	"	Indigarka River	1.0 – 10	–	–	Lomanchenkov (1959)
	UK	Endrick River, Scotland	0.5	25	2.0	Bluck (1971)
	"	River Arrow, Warwickshire	0.0326	–	–	Couper and Maddock (2001)
	"	"	0.0598	–	–	"
	"	Bradgate Brook, Leicestershire	0.15	–	–	Cummins and Potter (1972)
	"	River Lagan, Northern Ireland	0.076 – 0.14	–	–	Gardiner (1983)
	"	Clady River, Northern Ireland	0 – 0.5	2.0-3	0 – 16.67	Hill (1973)
	"	Crawfordsburn River, Northern Ireland	0-0.064	2.0-2.5	0 – 2.56	"
	"	Various streams, Devon	0.08 – 1.18	–	–	Hooke (1977)
	"	"	0.08 – 1.18	–	–	Hooke (1980)
	"	River Cound, Shropshire	0.64	17	3.76	Hughes (1977)
	"	River Bollin-Dean, Cheshire	0.29	–	–	Knighton (1972)

Table 1.2 – continued.

Climate	Country	Location	Bank Retreat Rate ($m\ a^{-1}$)	Width (m)	Retreat as a % of Width	Source
Cool temperate	UK	"	0.1 – 0.2	–	–	Knighton (1973)
	"	"	0.01 – 0.09	3-12	0.33 – 0.75	"
	"	River Ilston, Wales	~0.5	–	–	Lawler (1978)
	"	"	0.038 – 0.31	–	–	Lawler (1984)
	"	"	0.04 – 0.31	–	–	Lawler (1986)
	"	"	0.027	–	–	Lawler (1993b)
	"	Pennard Pill River, Wales	~1.25	–	–	Lawler and Bull (1977)
	"	Upper Severn River, Wales	0.013 – 0.46	Small	–	Lawler *et al.* (1997b)
	"	Swale-Ouse River, Northern England	0.071	"	–	Lawler *et al.* (1999)
	"	"	0.2	"	–	"
	"	"	0.317	"	–	"
	"	Afon Trannon River, Wales	0.03 – 0.96	NA	–	Leeks *et al.* (1988)
	"	River Rheidol, Wales	1.75	–	–	Lewin (1972)
	"	"	2.65	–	–	"
	"	Maesnant River, Wales	0.03	Small	–	Lewin *et al.* (1974)
	"	River Lagan, Northern Ireland	0.08 – 0.14	–	–	McGreal and Gardiner (1977)
	"	River Bollin, Cheshire	0.16	13	1.23	Mosley (1975)
	"	Narrator Brook, Devon	<0.03	Small	–	Murgatroyd and Ternan (1983)
	"	Monachyle Glen, Scotland	0.059	"	–	Stott (1997)
	"	Kirkton Glen, Scotland	0.047	"	–	"
	"	River Severn, Wales	0.35 – 0.6	–	–	Thorne (1978)
	"	"	0.015 – 0.02	Small	–	Thorne and Lewin (1979)
	USA	Yukon River, Alaska	>7.0	–	–	Eardley (1938)
	"	Little Missouri River, Dakota	1.7 – 7.0	91.5	1.86 – 7.65	Everitt (1968)
	"	Chemung River, Pennsylvania	3.05	–	–	Nelson (1966)
	"	Kenai River, Alaska	<0.3 – 1.5	–	–	Scott (1982)
	"	Colville River Delta	0 – 10.9	–	–	Walker *et al.* (1987)
Temperate	Australia	Gilgandra, New South Wales	0.004 – 0.053	<10	~0.04 – ~0.53	Crouch (1990)
	"	Various streams, New South Wales	0.005 – 0.075	<10	~0.05 – ~0.75	Crouch and Blong (1989)
	"	Snowy River, New South Wales	0.1	~180	0.06	Erskine (1996)
	"	Namoi River, New South Wales	0.33	–	–	Green *et al.* (1999)

Table 1.2 – continued.

Climate	Country	Location	Bank Retreat Rate (m a^{-1})	Width (m)	Retreat as a % of Width	Source
Temperate	Australia	Thurra River, Victoria	0.07	13	0.54	Marston *et al.* (2001) Prosser *et al.* (2001) Brooks (1999)
	“	Cann River, Victoria	4.5	66	6.82	
	“	Illawarra River, New South Wales	0 – 32.7	–	–	Nanson and Hean (1985)
	“	Ripple Creek, Tasmania	0.013	<10	~0.13	Prosser *et al.* (2000)
	“	Various streams, New South Wales	0.011	–	–	Soufi (1997)
	“	Torrens River, South Australia	0.58	5-10	5.8 – 11.6	Twidale (1964)
	Europe		<0.1 – 4.5	–	–	Knighton (1998)
	USA	Lower Ohio River, Kentucky	0.357	–	–	Alexander and Nunally (1972)
	“	Des Moines River, Iowa	>6.0	–	–	Allen (1895)
	“	Beaver Run, Pennsylvania	0.14	7.4	1.89	Allmendinger *et al.* (2005)
	“	Beaver Run, Pennsylvania	0.39	6	6.5	“
	“	Cobbs Creek, Pennsylvania	0.05	5.2	0.96	“
	“	Cobbs Creek, Pennsylvania	0.37	3.3	11.21	“
	“	Rocky Run, Pennsylvania	0.15	4.5	3.33	“
	“	Towamencin Ck Pennsylvania	0.02	6.9	0.29	“
	“	Towamencin Ck Pennsylvania	0.46	4.7	9.79	“
	“	East Fork River, Wyoming	0.06 – 0.08	–	–	Andrews (1982)
	“	White River, Indiana	0.67	–	–	Brice (1973)
	“	Middle Sacramento River, California	~4.6	–	–	Brice (1977)
	“	Various streams, Washington D.C.	0.1	10	1.0	Brice (1982)
	“	“	9.0	600	1.5	“
	“	Normal Brook, Indiana	0.59 – 0.94	–	–	Dryer and Davis (1911)
	“	Missouri River, Nebraska	15.2 – 152.4	–	–	Duncanson (1909)
	“	Kansas River, Kansas	23.9	–	–	Geyer *et al.* 2000
	“		47.3	–	–	“
	“	Various streams, Massachusetts	0.0	–	–	Goldthwaite (1937)
	“	Ohio River, Kentucky	5 – 15	–	–	Hagerty *et al.* (1981)
	“	Ohio River, Kentucky	0 – 1.5	–	–	Hagerty *et al.* (1983)
	“	Des Moines River, Iowa	6.6	–	–	Handy (1972)
	“	Fort Laramie National Monument, Wyoming	0.3	–	–	Hieb (1954)
	“	Lower Wabash River, Illinois	0 – 10	–	–	Jackson (1976)

Table 1.2 – continued.

Climate	Country	Location	Bank Retreat Rate ($m\ a^{-1}$)	Width (m)	Retreat as a % of Width	Source
Temperate	USA	Carmel River, California	0 – <1.2	–	–	Kondolf and Curry (1986)
	"	Watts Branch, Maryland	~0.5	–	–	Leopold (1973)
	"	"	~0.5	–	–	Leopold *et al.* (1964)
	"	Arroyo de los Frijoles, New Mexico	0.0057	<10	~0.057	Leopold *et al.* (1966)
	"	Sacramento River, California	4.2	382	1.1	Micheli *et al.* (2004)
	"	"	2.8	350	0.8	"
	"	Kern River (South Fork), California	0.25 – 1.5	30	0.83 – 5.0	Micheli and Kirchner (2002)
	"	East Nishnabotna River, Iowa	2.1 – 3.2	47-57	4.47 – 5.61	Odgaard (1987)
	"	Des Moines River, Iowa	2.4 – 3.7	199-204	0.015 – 0.051	"
	"	Brandywine Creek, Pennsylvania	0.19	42	0.45	Pizzuto and Meckelnburg (1989)
	"	Various streams, California	0.031	<10	~0.31	Reid (1989)
	"	Watts Branch, Maryland	0.45 – 0.6	~10	~4.5 – 6.0	Wolman (1959)
	"	Various streams, Maryland	0.075	–	–	Wolman and Leopold (1957)
Warm Temperate	USA	Mississippi River	23	Large	–	Brunsden and Kesel (1973)
	"	"	23	"	–	Carey (1969)
	"	"	48.2	"	–	Fisk (1951)
	"	"	<1.0 – >123	"	–	Hudson and Kesel (2000)
	"	"	6.8 – 18.9	"	–	Kesel and Baumann (1981)
	"	"	14.9 – 40.5	"	–	Kesel *et al.* (1974)
	"	"	0.61 – 305	1200	0.05 – 25.42	Kolb (1963)
	"	"	0.2 – 0.5	Large	–	Piest and Bowie (1974)
	"	"	4.6	"	–	Stanley *et al.* (1966)
Tropical	Zimbabwe	Zambezi River	0 – 7.9	Large	–	Guy (1981)
Wet tropical/ Monsoonal	India	Brahmaputra River	76	6000	0.1 – 4.58	Coleman (1969)
	"	"	262	13000	0.12 – 6.09	"
	"	Tapi River	0.75	570	0.13	Kale and Hire (2004)
	"	Brahmaputra–Jamuna River	160	10600	1.51	Khan and Islam (2003)

Table 1.2 – continued.

Climate	Country	Location	Bank Retreat Rate (m a^{-1})	Width (m)	Retreat as a % of Width	Source
Wet tropical/ Monsoonal	Nigeria	Niger River Delta	0.36	<150	~0.24	Okagbue and Abam (1986)
	Thailand	Yom River	0	Large	–	Bishop (1987)
	"	Mekong River	1.0 – 2.0	"	–	Rutherfurd and Bishop (1996)
	Zambia	Luangwa River	0 – 33	<200	0 – 16.5	Gilvear *et al.* (2000)
Subtropical	Peru	Ucayali, Amazon rivers	200	Large	–	Salo *et al.* (1986)
	"	Manu River	12	"	–	"

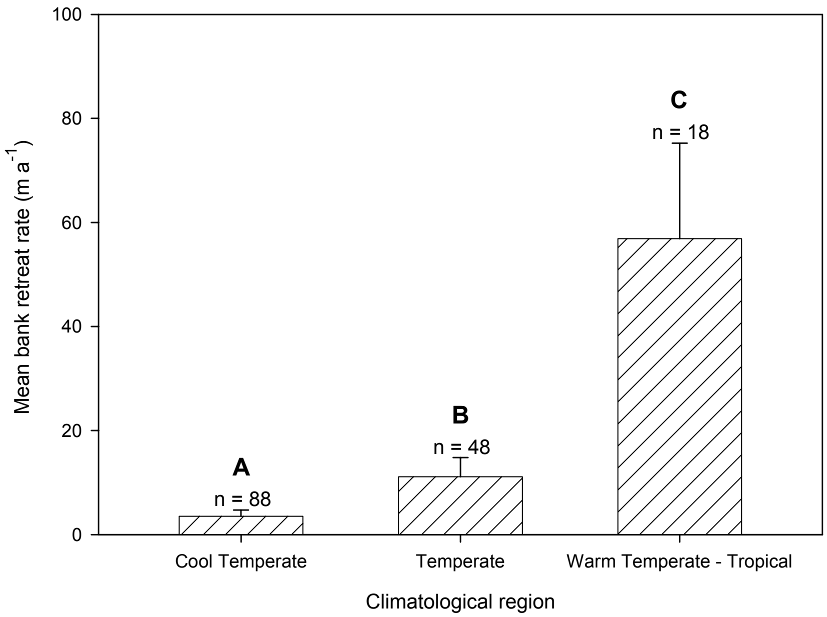


Figure 1.1 – Bank retreat rates in different climatological regions, derived from the literature.

Data derived from studies listed in Table 1.1. ANOVA: $F_{2,151} = 23.489$, $p < 0.001$; Tukey's test: A-B, $p = 0.787$; A-C, $p < 0.001$; B-C, $p < 0.001$.

Climatologically based classification of streams and rivers is used in the present review as opposed to a hydrologically based classification as suggested by Beckinsale (1969), Gentilli (1952) and Haines *et al.* (1988) because of a paucity of hydrological data for these streams. There are numerous examples of gauged streams/rivers worldwide (Haines *et al.* (1988) list 969 stream gauging stations in 66 countries) and similarly extensive research on bank retreat rates. However, examples of bank retreat data described in association with seasonal and annual hydrological data are limited because, in many instances where gauge data is available, their positioning in the study streams makes them inadequate for use in bank erosion studies. Climate and its links with vegetation, sediment, rock structure, catchment size and morphometry and hydraulic geometry determines a river's hydrological regime (Beckinsale 1969, Haines *et al.* 1988). Thus, climate can provide a general indicator of a stream's hydrological regime, regardless of any variability that may exist with regard to local factors and the position in the catchment.

1.5.3 Cool temperate studies

The majority of studies focussing on bank retreat rates have been undertaken in temperate and especially cool temperate regions (Table 1.2). Rates of streambank retreat in streams draining cool temperate catchments are variable because of the variability in local and regional driving forces. For example, Crickmay (1960), Hickin and Nanson (1975, 1984) and Nanson and Hickin (1983, 1986) reported varying degrees of bank retreat in streams and rivers in British Columbia and Alberta, Canada (0-12.6 m a^{-1}) but attributed the rates of retreat to various parameters, including curvature, bank height, vegetation and discharge. Numerous British studies have shown large variations in, but slower rates of, bank retreat, with rates ranging between 0 m a^{-1} and 2.65 m a^{-1} (e.g. Bluck 1971, Couper and Maddock 2001, Knighton 1973, Lawler 1993b, Lawler *et al.* 1999, Lewin 1972, Stott 1997). These studies also suggested similarly variable local bank retreat driving forces. The effect of the variability of driving forces on retreat is dealt with further in Section 1.5.7. Reported rates may also vary according to the method used. Hickin and Nanson (1975), for example used meander bend scroll bars to measure retreat, while Lawler (1993b) used erosion pins – methods of very different scales. This issue is also examined in Section 1.5.7.

1.5.4 Temperate and warm temperate studies

Fluvial systems in temperate and warm temperate zones experience similarly variable rates of bank retreat. The causes of this retreat are also variable. However, the variability in retreat may not necessarily be attributed to the same bank retreat driving forces – different regions will be subject to different conditions and so the processes and characteristics responsible for retreat may differ accordingly. Rates of retreat of streams that drain temperate Australian catchments (NSW and Victoria) vary from 0.0004 m a^{-1} to 4.5 m a^{-1} (Brooks 1999, Erskine 1996, Prosser *et al.* 2001); reported retreat rates of streams in temperate regions of the USA vary between 0.057 and 9.0 m a^{-1} (Brice 1982, Micheli and Kirchner 2002, Odgaard 1987, Reid 1989); and studies on the warm temperate Mississippi River in the USA, showed river reaches experiencing large and highly variable bank retreat, ranging between 0.61 and 305 m a^{-1} (Brunsden and Kesel 1973, Carey 1969, Hudson and Kesel 2000, Kesel *et al.* 1974, Kolb 1963). These high rates are most probably largely due to the size of the Mississippi system – larger systems tend to experience larger, more erosive flows that cause larger-scale retreat (Lawler *et al.* 1999).

1.5.5 Sub-arctic studies

Only one study from this region was found. Kulemina (1973) found large variations in lateral bank retreat on reaches of the Ob River in Siberia, ranging between 0 m a^{-1} and 15 m a^{-1}.

1.5.6 Tropical/monsoonal studies

The few studies that have taken place in tropical zones report high rates of bank retreat, but there is considerable variation between and within different fluvial systems (0-200 m a^{-1}) (Bishop 1987, Gilvear *et al.* 2000, Guy 1981, Okagbue and Abam 1986, Rutherfurd and Bishop

1996, Salo *et al.* 1986). Extensive research of monsoon-fed river systems in India and Bangladesh have also shown variable rates of retreat, with Coleman (1969), Kale and Hire (2004) and Khan and Islam (2003) measuring rates of bank retreat between 0.75 m a^{-1} and 262 m a^{-1}.

1.5.7 Variability of streambank retreat rates

Because of the large variability of bank retreat rates within regions, it is difficult to identify firm patterns between regions. The studies in Table 1.2 do not necessarily encompass the full range of bank retreat/erosion rates, but they indicate the extensive and variable nature of bank retreat and erosion in all climatological regions. Nanson and Hickin (1986), Hudson and Kesel (2000), Odgaard (1987), and Prosser *et al.* (2000) have shown that rates of bank retreat can also vary considerably within small geographical regions, within rivers and between adjacent meander bends on the same stream. This is not unexpected given the spatial scales over which critical environmental parameters may vary, but suggests that reported rates are affected by local and regional factors, including the study site location and its particular attributes, the type of bank retreat that is occurring, as well as being influenced by the data collection methods (Prosser *et al.* 2000). Identification of the critical factors, their variability and their effect on the patterns of bank retreat variability that occurs is the focus of this thesis. These factors are considered below.

<u>Methods and their effect on measures of retreat rate</u>

Hooke (1980) discussed three main methods that can be used to measure rates of bank retreat: (1) field measurements; (2) examination of maps and aerial photographs of different dates; and (3) datable sedimentary or biological evidence. Lawler (1993a) used a similar classification scheme, but divided field measurement into planimetric resurveys, repeated cross-profiling, use of erosion pins and repeated terrestrial photogrammetric surveys. Lawler (1993a) also discussed several other methods, including morphological evidence, local knowledge, hydrographic resurvey, sediment traps, repeated photography, painted sections and erosion boxes, and Lawler (1989, 1991, 1992, 1993a) discussed the use of bank-installed electronic sensing erosion measurement equipment (Photo-Electronic Erosion Pin – PEEP) as another mechanism for measuring bank retreat rates. The different methods used to measure bank retreat, and their applications and usage are presented in Table 1.3, along with examples of studies that have employed each method.

Table 1.3 – Bank retreat measurement methods, their applications and their users

Bank Retreat Measurement Method*	Applications	Usage	Examples Of Research Using Method
Historical maps/aerial photographs	Long-term change (150 years) Accuracy varies according to map/photo scale and length of time intervals between sources	Very common	Alexander and Nunally (1972), Bluck (1971), Brice (1973), Brizga and Finlayson (1990), Brooks and Brierley (1997), Brunsden and Kesel (1973), Carey (1969), Coleman (1969), Crickmay (1960), Geyer *et al.* (2000), Green *et al.* (1999), Handy (1972), Hooke (1984), Hudson and Kesel (2000), Klimek and Trafas (1972), Kolb (1963), Kondrat'yev (1968), Kondrat'yev and Popov (1967), Kulemina (1973), Laczay (1977), Lewin (1972), Micheli *et al.* (2004), Mosley (1975), Pizzuto and Meckelnburg (1989), Rutherfurd and Bishop (1996), Sundborg (1956), Wolman (1959)
Surveying (Profiles/planimetric)	Medium-term change (0.5 – 30 years) Small to medium scale bank retreat	Very common	Allen (1985), Allmendinger *et al.* (2005), Andrews (1982), Bray (1987), Dryer and Davis (1911), Duysings (1986), Green *et al.* (1999), Guy (1981), Hagerty *et al.* (1983), Hooke (1977), Hughes (1977), Kale and Hire (2004), Karasev (1964), Kesel and Baumann (1981), Knighton (1972), Kondolf and Curry (1986), Lawler (1984), Lawler and Bull (1977), Leeks *et al.* (1988), Leopold (1973), Lomanchenkov (1959), Nanson and Hean (1985), Piest and Bowie (1974), Stanley *et al.* (1966), Thorne (1978), Williams *et al.* (1979), Wolman (1959), Wolman and Leopold (1957)
Erosion pins	Short-term change (months to a few years) Emphasis on individual processes and events Small-scale bank retreat	Very common	Couper and Maddock (2001), Cummins and Potter (1972), Duijsings (1987), Duysings (1986), Hagerty *et al.* (1983), Hill (1973), Hooke (1977), Imeson and Jungerius (1974), Ireland *et al.* (1939), Knighton (1972), (1973), Laubel *et al.* (2003), Lawler (1978), (1984), (1986), Lewin *et al.* (1974), McGreal and Gardiner (1977), Murgatroyd and Ternan (1983), Prosser *et al.* (2000), Thorne (1978), Twidale (1964), Wolman (1959)
Photo-Electronic Erosion Pin	As for erosion pins	Increasing	Lawler (1989, 1991, 1992, 1993a), Lawler *et al.* (1997b), Lawler *et al.* (1999)
Sedimentological evidence	Long-term change (50 – 15000 years) Large-scale channel change	Common	Alexander and Nunally (1972), Bluck (1971), Everitt (1968), Fisk (1951), Kolb (1963), Laury (1971), Nanson (1986)
Botanical evidence	Long-term change (50 – 1000 years) Large-scale patterns of change	Rare	Alexander and Nunally (1972), Eardley (1938), Everitt (1968), Hickin and Nanson (1975, 1984), Nanson and Beach (1977), Nanson and Hickin (1983)
Terrestrial Photogrammetry	As for erosion pins	Rare	Dickinson and Scott (1979)
Morphological evidence	Inference of change (low accuracy)	Rare	Hickin (1974), Kondrat'yev (1968), Nanson (1980)
Local opinion	Inference of change (low accuracy)	Rare	Kondolf and Curry (1986)

Table 1.3 – continued.

Bank Retreat Measurement Method	Applications	Usage	Examples Of Research Using Method
Thermal disturbance	Long-term change (< 500 years) Large-scale rough estimates of change	Rare	Smith and Hwang (1973)
Hydrographic resurvey	Subaqueous bank recession Medium-term change Small- to medium- scale retreat	Rare	Stanley *et al.* (1966)
Sediment traps	Short-term estimation of removal of sediment and inferred retreat rate Small-scale bank retreat	Rare	Hill (1973), Lawler (1984)
Repeated photography	In place of surveying	Rare	Harvey (1974)
Painted sections/pebbles	Identification of erosion location	Rare	Thorne (1978)
Erosion box	Estimation of erosion susceptibility	Rare	Smith (1976)

* Lawler (1993a) provides descriptions of these methods

Differences in technology levels, scale, accuracy and assumptions associated with different methods can influence reported bank retreat results (Lawler 1993a). The advantages and disadvantages of different methods for measuring bank retreat rate are highlighted when comparing the two most consistently used methods: maps/aerial photography and erosion pins. Both methods provide simple, cost-effective measures of bank retreat and have been widely applied. For example, Alexander and Nunally (1972), Brice (1973) and Kulemina (1973) used maps to determine bank retreat rates, and Brizga and Finlayson (1990), Hudson and Kesel (2000) and Rutherfurd and Bishop (1996) used historical aerial photography to identify locations and rates of retreat. Alternatively (or in conjunction with maps/aerial photography), erosion pins have been used by Couper and Maddock (2001), Hill (1973), Lawler (1986, 1992), and Prosser *et al.* (2000). Both methods are useful in determining rates of erosion, but can be difficult to compare because of the differences in scale between them: erosion pins provide precise estimates of short-term local-scale erosion, whereas maps/aerial photography identify large-scale bank retreat over longer periods of time and at large scales. In effect, this means that relative to the highly accurate measurements of erosion pins, maps/aerial photography often provide only approximate retreat data as they are limited by their pixel size. However, over time, they integrate long-term change and are more geographically extensive.

Other problems in comparing results from different methods typically involve differences in spatial and chronological scale. For example, Lawler *et al.* (1997b) and Lawler *et al.* (1999) identified rates of bank retreat of < 0.5 m a^{-1} using erosion pins, but use of satellite imagery or aerial photography (see Salo *et al.* 1986) could not have identified erosion of this magnitude because of the relatively low resolution of the technique. Similarly, while erosion pins measure actual erosion rates for a discrete interval or event, satellite imagery determines average rates of retreat between image intervals.

Therefore, the degree of error associated with different techniques is an important issue. Downward *et al.* (1994) and Mount and Louis (2005) noted that any retreat identified is only useful if it exceeds the error in the measurement process. Pins, cross-profiling and other fine-scale techniques measure changes with millimetre accuracy and report errors of similar scale (Lawler 1978, Lawler and Leeks 1992). The technology of aerial photography and GIS analysis are rapidly improving and becoming more applicable to measuring fine-scale bank retreat; however, these techniques may introduce far more error than traditional fine-scale techniques.

Distortion of images is a major problem introduced with the use of aerial photography (Green *et al.* 1999, Lawler 1993a). Distortion increases with distance from the centre of the photograph, so retreat rates observed in the photograph vary over the area of the photo. Thus, if photographic flight plans remain constant, as a hypothetical channel migrates at a consistent rate across a floodplain, it may be perceived to migrate at varying rates. Retreat measurement error is also introduced with the use of photographic enlargement techniques. These are used to ensure comparisons are made between images of the same scale. Gurnell (1998) used images of different scale to analyse channel change on the River Dee, UK. However, enlarged photographic images are difficult to interpret and are often unrepresentative of actual features. Methods to minimise the effects of distortion and enlargement do exist (see Gurnell 1998), but error is still introduced into measurements of bank retreat.

Of most concern, however, are not the failures of the technology, but the difficulty in observing actual bank positions, such as the channel edge (Gurnell 1997, Gurnell *et al.* 1994) because of morphological differences in the channel-floodplain interface, scale issues identified above and problems created by riparian vegetation. Gurnell (1998) used riparian vegetation edge to define the channel, explaining that it was clearly identifiable except where there were overhanging trees. Yet, there are practical and technical challenges to working in riparian environments. In regions of dense vegetation, such as the wet tropics, the edge of the riparian vegetation and therefore the channel can be impossible to identify (Louez 2004), while surveying techniques can be ineffective because of the lack of a line-of-sight.

It is important that appropriate methods are applied to suit the physical conditions and aims of the research. It is also important to be aware of the limitations of any approach when interpreting the data. For example, while erosion pins and accurate surveying (using Electronic Distance Measurement instruments (EDMs)) often give similarly accurate readings of local-scale bank erosion, Couper and Maddock (2001) and Lawler (1993a) both report bias in results arising from the loss of pins in large events. The use of permanent reference markers reduces these problems. Thus, erosion pins would be inappropriate for a large system eroding at a rate of metres per event, while the use of maps and aerial photography to measure erosion of the bank face of small first order streams would also be ineffective.

Development in measurement methods can often improve the ability of a technique to measure different types and rates of erosion. For example, improvements to pin technology (Lawler 1989, 1991, 1992, Lawler and Leeks 1992, Lawler *et al.* 1997b) have lowered likelihood of pin removal and have increased their durability in larger systems, while improvements to surveying techniques (introduction and further technological upgrades to EDMs) have improved accuracy related to staff positioning and distance and height measurement, and thus have improved their potential for providing a reliable alternative to pin techniques in medium to large fluvial systems.

Location effect on retreat rates

Reported rates of bank retreat vary between geographic and climatological regions (Section 1.5.2), but also between sites on the same stream (e.g. Couper and Maddock 2001, Hooke 1980, Laubel *et al.* 1999, Prosser *et al.* 2000). For example, Wolman (1959) showed differences between sites at the ends of a meander loop (0.7 m of retreat in two months for upstream site compared with 0.46 m for the downstream site), while Odgaard (1987) observed variable rates (1.0-7.0 m a^{-1}) of bank retreat on different parts of a stream reach in Iowa. These variations in rates of bank retreat are due to the variable local and regional conditions that occur as a result of the location of a stream. Local-level controls (e.g. bank material, bank geometry) are especially important in determining the local bank retreat rates (Hudson and Kesel 2000).

Impact of prevailing conditions on retreat rates

Hickin and Nanson (1975) incorporated some of the factors that can act to determine bank retreat rates in their equation:

$$M = f(Q, s, c, h, v, r_m/w_m)$$

where M = lateral migration, Q = discharge, s = water-surface slope, c = character of boundary material, h = bank height, v = bank vegetation and r_m/w_m = curvature (channel radius/width). In essence, however, the general causes of bank retreat are the interaction between shear strength and stress and the duration over which a certain threshold is exceeded as a result of these interactions. These interactions are largely influenced by a variety of interrelated sedimentological, hydrological, geomorphological and vegetative factors, and are discussed below.

Scale

Scale influences rates of bank retreat and associated lateral stream migration in several ways. The larger cross-sectional area and discharges, and higher banks associated with larger stream systems can result in higher rates and different types of bank retreat (Abernethy and Rutherfurd 2000b, Lawler *et al.* 1999). Brice (1982), Hooke (1980), and Nanson and Hickin (1986), for example, showed that channel width, as an indication of stream size, affected bank retreat rates. Brice (1982) found that bank retreat was 0.1 m a^{-1} in a 10 m wide stream system compared with 9.0 m a^{-1} for a 600 m wide channel. This effect of stream size on bank retreat rates is illustrated for 64 studies that include corresponding width and bank retreat rate data in Figure 1.2, which shows a moderate, logarithmic relationship between the width and retreat rate data. Brice

(1982) also found a linear relationship between mean bank retreat rates and channel width, with rates approximating to 0.01 times channel width.

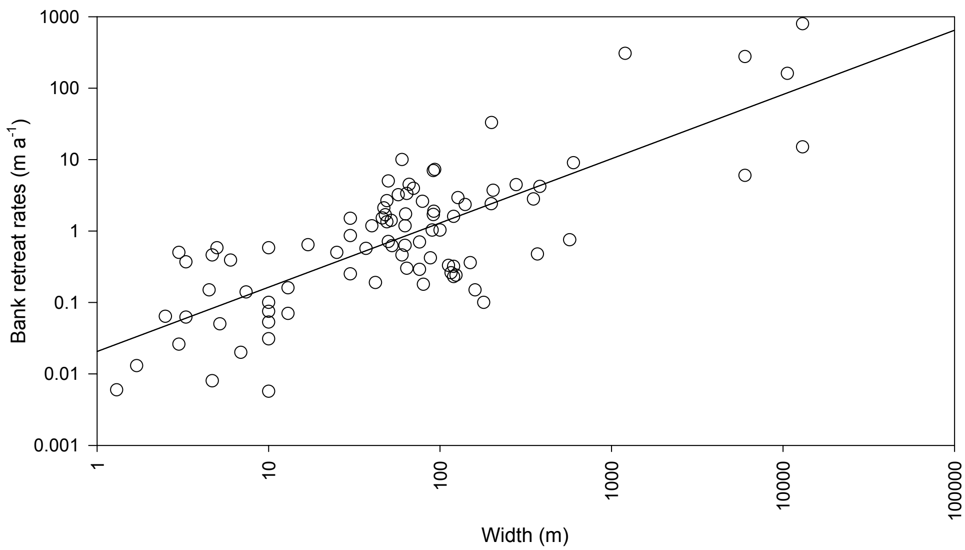


Figure 1.2 – Relationship between bank retreat rates and stream width.
Regression results: log y = log(0.89x) - 1.68; $r^2 = 0.60$; $p < 0.05$. Data compiled from studies listed in Table 1.2.

Most studies using drainage area as a surrogate for stream size show similar results. Figure 1.3 shows the results of a regression between the drainage areas and rates of bank retreat reported in the literature. It shows a similar logarithmic relationship to that illustrated in Figure 1.2. Hooke (1980) gives good contrasting examples of bank retreat of 0.05 m a^{-1} in a catchment area of 3 km^2 and bank retreat in the order of 800 m a^{-1} for a catchment area of 1,000,000 km^2. Hooke (1980) also showed that drainage area explained 53% of erosion rate variation. Other research has shown similar results – Lawler *et al.* (1997b) showed erosion rates increasing (0.13 m a^{-1} – 0.46 m a^{-1}) with distance downstream, Odgaard (1987) showed erosion rates of 2.8 m a^{-1} in the upper stream reaches and 3.2 m a^{-1} for the downstream reaches, while Hudson and Kesel (2000) measured bank retreat of 5.7 m a^{-1} on the upstream reaches of Mississippi River and 45.2 m a^{-1} on the downstream reaches.

However, using drainage area as a surrogate for stream size is not always satisfactory, as stream dimensions rarely increase linearly downstream from the source. For example, stepwise changes in stream size exist below tributaries and with structural breaks in slopes. Numerous circumstances also exist where local factors limit bank retreat and change. For example, some streams of the Illawarra region of New South Wales exhibit downstream reductions in channel size, attributed largely to the rapid decline in slope and stream power, the availability of floodplain overbanking and the cohesive nature of the bank sediments (Nanson and Young 1981). Underlying geology, sediment type and geological formations all provide limitations to bank retreat and changes in channel dimension. This is the case in coastal streams of northern Queensland, where the channel dimensions of many streams actually decrease on the floodplain close to the coast (Kapitzke *et al.* 1996). The channel dimensions of both Russell and Mulgrave Rivers in north-eastern Queensland, for example, are limited by hard remnant coastal mountains and some reaches are unable to move laterally. Thus, while drainage area increases downstream, the potential discharge carried by these channels and their related stream power actually decreases.

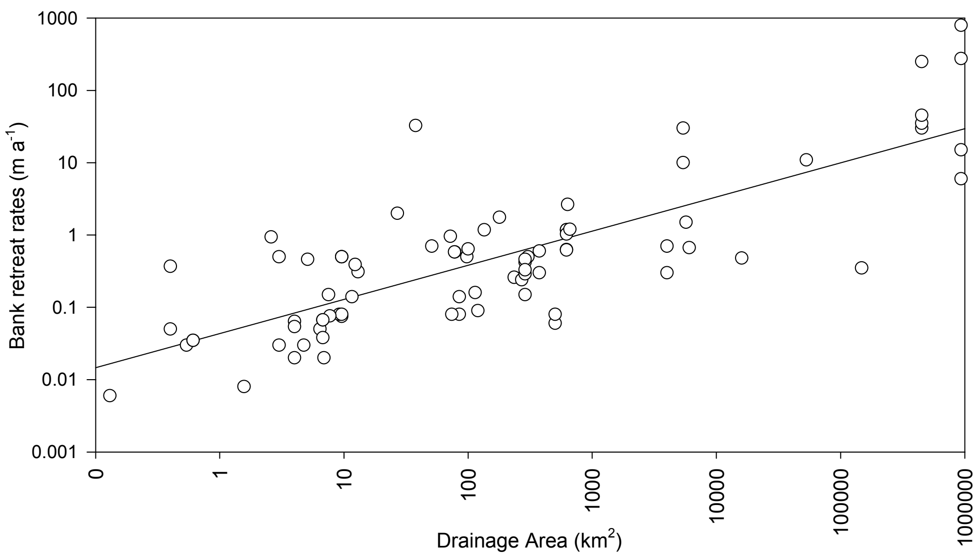


Figure 1.3 – Relationship between bank retreat rates and drainage area.
Regression results: log y = log(0.47x) - 1.36; r2 = 0.63; $p < 0.05$). Data from Hooke (1980), Hudson and Kesel (2000) and Lawler (1993a).

There are obvious difficulties in comparing results of studies from streams of different sizes, as indicated by the relationships between stream size and bank retreat above. Instead, a measure of bank retreat relative to stream size needs to be used to illustrate comparative retreat (bank retreat/width of stream, bank retreat/drainage area). Figure 1.4 illustrates the relationship between width and bank retreat rates as a percentage of width. It indicates that the relative importance of width (i.e. size) is minimal. For example, Coleman (1969) measured bank retreat of up to 792 m a^{-1} on the Brahmaputra River, but this only represented 6.09% of the channel width (13,000 m), indicating that the significance to the entire system is much less than the movement suggests, although that degree of movement is of obvious importance at the local level. An example of smaller rates of bank retreat (4.5 m a^{-1}) is reported by Marston *et al.* (2001) for the Cann River, Australia; however, the relative significance of this bank retreat (6.82% of its 66 m width) to the system is similar to that of the Brahmaputra River because of its smaller channel width.

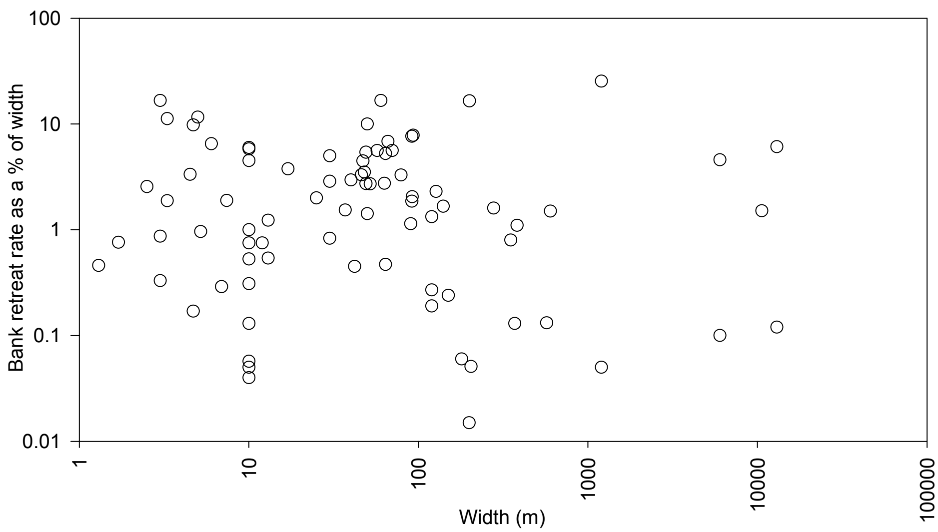


Figure 1.4 – Relationship between channel width and relative bank retreat.
No significant relationship was identified ($r^2 = 0.01$; $p > 0.05$). Data compiled from studies listed in Table 1.2.

Discharge and velocity

Discharge and velocity are often linked with erosion rates and are used in bank retreat studies to provide a good indication of the potential of a flow to perform geomorphic work. Indeed, both erosion and sedimentation are largely explained by flow inundation and duration, and flow velocities/discharge in the stream channel (Hooke 1980, Kale 2003, Lawler *et al.* 1997b). In most studies, increasing bank retreat rates are associated with increasing discharge (as with increasing width/drainage area). Walker and Rutherfurd (1999), for example, identified a power relationship between discharge and bank retreat in their second approximation analysis of a global data set. Ikeda *et al.* (1981), and Pizzuto and Meckelnburg (1989) demonstrated a clear link between bank erosion and bankfull (high) velocities. Similarly, Hooke (1980), Klein (1981) and Lawler *et al.* (1997b) identified discharge as a primary natural variable affecting erosion. Other aspects of velocity and discharge, such as flow duration, are also critical in determining rates of bank retreat by affecting the amount of time for which geomorphic work is performed (Costa and O'Connor 1995).

Channel planform curvature

Channel planform curvature affects bank retreat as it influences the degree of shear stress that is focussed on the bank face. It is recognized as having a complex non-linear relationship with bank retreat rates. There are two main models of the curvature-bank retreat relationships. The first model was developed by Hickin (1974) and Hickin and Nanson (1975) and shows that bank retreat rates increase dramatically as curvature increases, reaching a maximum at a curvature of 2.5-3.0 before tapering off more gradually (Figure 1.5). There has been subsequent support for this model (Ferguson 1989, Gilvear *et al.* 2000, Hooke 1996, Hooke 1997). An r_m/W_m equilibrium value of between 1.5 and 4.3 appears to apply to this model, suggesting that meanders sustain this equilibrium form while undergoing downstream translation (Knighton 1998); however, the evolution of a meander bend from one of low curvature towards a highly tortuous form and eventual cutoff is also a likely explanation (Hooke 1987).

The second model was developed by Hudson and Kesel (2000). It generally follows a similar non-linear relationship; however, it peaks at a curvature of approximately one (compared with 2-3) (Figure 1.6). The differences between models are largely attributed to differences in local factors, especially bank sediment characteristics. Hudson and Kesel (2000) proposed that the major difference between their study and those of Hickin (1974) and Hickin and Nanson (1975) was the heterogeneity of their study banks (Hickin (1974) and Hickin and Nanson (1975) had noted that a limiting factor of their study was the homogeneous nature of their study banks). The restrictive nature of some bank sediment makes it impossible for downstream translation of meanders, altering their growth and formation and so resulting in more arch-shaped (lower curvature value) meander bends (Hudson and Kesel 2000). Regardless of which model applies to a particular setting, it is clear that curvature plays a large role in determining bank retreat rates and, in turn, retreat rates affect curvature. Given the heterogeneous nature of many north-eastern Queensland streams, it is expected that bank retreat rates in the current study will conform to a curvature relationship similar to the one proposed by Hudson and Kesel (2000).

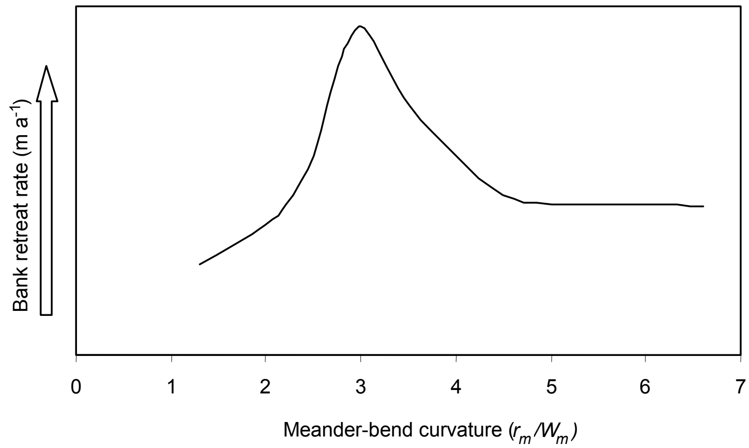


Figure 1.5 – Conceptual model 1 of channel curvature and notional bank retreat (after Hickin (1974) and Hickin and Nanson (1975)).

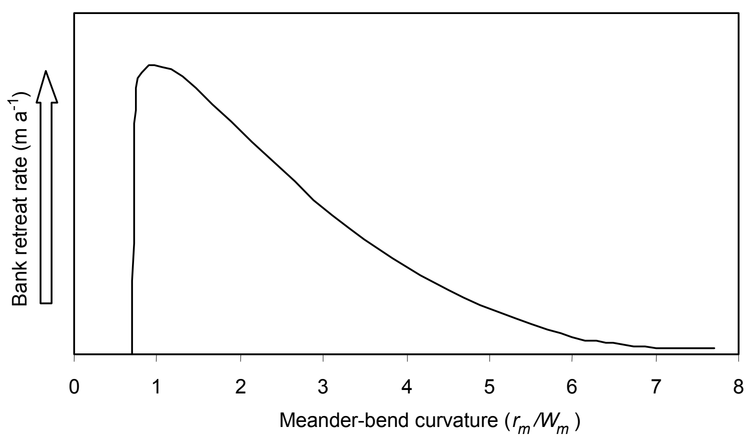


Figure 1.6 – Conceptual model 2 of channel curvature and notional bank retreat (after Hudson and Kesel (2000)).

Bank geometry

Bank retreat rates can be affected greatly by bank dimensions (angle, height) (Abernethy 1999, Dapporto *et al.* 2003, Thorne 1991). Bank height and angle influence retreat rates by determining the degree of bank exposure to fluvial processes, controlling bank weight and associated stability and controlling effective root depth (Abernethy 1999, Dapporto *et al.* 2003, Ponce 1978, Thorne 1991). Laubel *et al.* (2003) used stepwise regression and empirical models to show that high bank angle was the predominant factor causing bank retreat, while Abam and Omuso (2000), using a deterministic sensitivity technique, concluded that bank slope was an important variable in determining cross-sectional change. Dapporto *et al.* (2003) and Osman and Thorne (1988) attributed lateral bank retreat to a suite of factors, among which high bank heights and angles ranked highly and Twidale (1964) linked greater bank retreat to the steeper bank sections.

Bank materials

There are examples of the influence of bank material on bank retreat from a wide range of locations. Hooke (1987) found that heterogeneous banks of the River Dane, England, altered the model linking curvature and bank retreat rate suggested by Hickin and Nanson (1975), while Ebisemiju (1994), Ferguson (1987), Odgaard (1987) and Schumm (1963) found a strong positive relationship between bank material cohesiveness and sinuosity and its related bank retreat. Similarly, Green *et al.* (1999), Hudson and Kesel (2000), Laubel *et al.* (1999) and Prosser *et al.* (2000) found that more resistant material reduced channel mobility and associated meander development. Fisk (1947) showed that resistant clay deposits (plugs) affected meander bend shape; Hudson and Kesel (2000) demonstrated that these plugs reduced bank retreat rates; and Dapporto *et al.* (2003) and Thorne and Tovey (1981) demonstrated a link between sediment size and bank stability.

However, it is the interaction between different bank sedimentary units and bank height and angle (stratigraphy) that is of most interest with regard to control of bank retreat. Resistance provided by certain sedimentary units and the lack of resistance provided by others influences bank geometry and, thus, bank retreat. Finer-grained cohesive basal sedimentary units that provide resistance to flow can prevent oversteepening of the bank and related bank retreat (Gilvear *et al.* 2000, Nanson and Hickin 1986, Okagbue and Abam 1986). Thus, in a study of the Sieve River, Italy, Rinaldi and Casagli (1999) showed that banks with a lower gravel stratum and upper silty-sand stratum were more likely to undergo toe erosion, steepen and become unstable.

Vegetation

Bank vegetation appears to have direct and subsidiary influences on bank retreat through its interaction with other bank characteristics. Abernethy and Rutherfurd (2000a), Murray and Paola (2003), Simon and Collison (2002) and Thorne (1990) discuss the benefits of vegetation to streambank stability. The extent to which vegetation affects retreat rates, however, is still largely unknown. Most available studies of retreat rates have shown that vegetation has played some part (ranging from very little to major impacts) in determining rates, at a variety of scales.

At a reach scale, vegetation has been identified as an impediment to bank retreat, and the removal of vegetation can be responsible for channel disequilibrium and metamorphosis (Brooks and Brierley 2002). Allmendinger *et al.* (2005) compared adjacent forested and non-forested reaches in Pennsylvania and found that lateral bank retreat was three orders of magnitude lower in the forested reaches. Likewise, Micheli *et al.* (2004) showed that banks exposed by clearance of riparian vegetation on the Sacramento River in California were 80-150% more erodible than uncleared banks. These studies often lack data with regards to roots, bank stratigraphy and hydrology, but provide clear evidence of relationships between vegetation and retreat.

At a site scale, vegetation characteristics have been shown to protect banks against erosional processes. Vegetation has a three-fold effect on bank stability: it directly strengthens the bank through its contribution to increased sediment cohesion, it encourages sediment aggregation with the introduction of organic matter, and protruding roots slow primary and secondary flow adjacent to the bank (Abernethy and Rutherfurd 1999b). Bank resistance can increase by more than one order of magnitude with the addition of a dense root network (Hickin and Nanson 1984, Thorne 1990). Abernethy and Rutherfurd (1999a), for example, observed bank stability improvements on the Latrobe River in Victoria associated with the addition of river red gum and swamp paperbark tree roots.

However, Nanson and Hickin (1986) and Pearson (1999) found only limited stabilising effects of vegetation. Nanson and Hickin (1986) observed distinct undercutting of vegetation-ridden banks and resulting bank retreat, while Pearson (1999) found no significant differences in erosion between naturally vegetated stream reaches and cleared reaches in a tropical Australian stream. Thus, the influence of vegetation on bank retreat, like other factors, is different in different systems, but is clearly a factor that must be considered in any study of bank retreat.

While discussion of the enhanced cohesion and inherent stability provided by well vegetated banks of particular tree species is widespread (Abernethy 1999, Abernethy and Rutherfurd 2001, Phillips *et al.* 2001, Simon and Collison 2002, Yarbrough 2000), there has been little research on root-enhanced stability conducted *in situ* at the bank-channel interface. This lack of investigation is typically due to 1) the assumption that root density and resultant enhanced stability will not vary greatly between the bank edge and further away; and 2) *ex situ* studies are far easier and more cost-effective as excavation is easier on dry land than in a wet channel. However, as most banks are vegetated by several species, it might be argued that stability/erosion studies should consider root characteristics of all species that inhabit the bank of interest. Furthermore, because of the different conditions experienced at the bank edge and on the floodplain (increased presence of water, inundation, flow disturbance), root density is likely to be different. This is alluded to by studies on the uptake of water by plants: for example, root densities vary between species (Simon and Collison 2002) and sediment type (Sainju and Good 1993) and are influenced strongly by the hydrological properties of sediments (Bending and Moffat 1999). However, because neither this difference nor the contribution of community roots to enhanced stability have been quantitatively tested, there is major opportunity for *in situ* studies to assess the contribution of roots to bank stability.

<u>Other conditions</u>

There are several studies in which bank retreat has been linked to other prevailing conditions. Hickin and Nanson (1975) included channel slope as an important variable in their bank retreat model, and Ebisemiju (1994), Hudson and Kesel (2000), Richards (1972), and Schumm (1963) all recorded increasing bank retreat rates associated with increases in slope. Other researchers have discussed the effect of human activities on bank retreat rates (e.g. urban areas/agriculture/ grazing) (Larsen and Greco 2002, Laubel *et al.* 1999). Additionally, the effect of duration of data collection and when the study is occurring must be important considerations (Couper and Maddock 2001).

The effect of the duration of the data collection period is of great importance due to temporal controls of bank retreat. The magnitude/frequency debate discussed initially by Wolman and Miller (1960) suggests that it is not necessarily the largest flows that perform the most geomorphic work. Indeed, some large-magnitude events result in relatively little geomorphic work (e.g. Meyer 2001). Short-term studies of the effects of a few large-magnitude events can result in retreat rate data of contrasting magnitudes from longer-term studies. Hooke (1980), Twidale (1964) and Wolman (1959) all found that short-term bank retreat rates were of a higher magnitude than historical long-term rates. This finding is partly because observations from short-term studies do not adequately represent some longer-term driving forces (Couper 2004). This point is especially prevalent in particular climatological/hydrological regimes (e.g. northeastern Queensland, monsoon-fed streams) where streams are subject to frequent extreme discharges that can perform significant geomorphic work that results in lasting channel change (Amos *et al.* 2004, Kale 2003).

1.5.8 Types of bank retreat and migration

Bank retreat may occur because of a variety of mechanisms, including subaerial preparation, scour or failure mechanisms. The different mechanisms studied will affect the reported rate of retreat. Rates of 0.326 m a^{-1} via subaerial preparation and 0.598 m a^{-1} by means of fluvial scour and mass failure measured on the River Arrow in the United Kingdom illustrate these differences (Couper and Maddock 2001).

Recorded rates of channel retreat as a result of meander cut-offs, avulsion (complete shift in channel position) or anabranching (branch of a stream that re-enters main channel) are all high compared with studies of bank retreat mechanisms (e.g. Brizga and Finlayson 1990). For a stream reach experiencing meander cut-off, the gradual retreat causing cut-off may represent a retreat of small magnitude, but the 'net' rate of retreat from the tip of the meander loop to the cut-off location can be much greater. Avulsions can also exaggerate reported rates of bank retreat. Brizga and Finlayson (1990) showed that avulsion on the Thomson River accounted for 2.5 km of retreat within one year. Gradual scour would not have accounted for such high rates. Avulsions and cut-offs also affect downstream bank retreat rates by increasing gradients and stream sediment loads (Handy 1972, Howard and Knutson 1984, Kulemina 1973, Nanson and Hickin 1983). Other forms of movement, such as confined migration, anabranching and growth and compound development, may result in varying reported rates of retreat.

1.5.9 North-eastern Queensland and tropical studies

There has been limited research undertaken in tropical regions (Table 1.2). For example, Okagbue and Abam (1986) measured low rates of bank retreat (<1.0 m a^{-1}) on Ekole Creek, Nigeria, Gilvear *et al.* (2000) and Guy (1981) showed variable bank retreat rates (0 m a^{-1} – 33 m a^{-1} and 0 m a^{-1} – 7.9 m a^{-1} respectively) on two tropical African systems, while Salo *et al.* (1986) observed high stream mobility on the Manů River (12 m a^{-1}) and on the Amazon and Ucayali (up to 200 m a^{-1}) in Peru. However, there is a distinct shortage of quantitative as opposed to descriptive research in the tropics (e.g. Chitale 1970, Holz and Baker 1981 and Savat 1975).

North-eastern Queensland is an example of one of the less-studied tropical regions. Studies of streams in this region are important locally due to their relevance to local management issues but are also important in a global context as they provide case studies in poorly represented hydrologically active regions. North-eastern Queensland provides an excellent location to study streambank erosion in relation to riparian vegetation controls because of the prevalence of riparian corridor fragmentation within much of the coastal floodplains (Bunn *et al.* 1998, Kapitzke *et al.* 1996), allowing direct comparisons between vegetated and unvegetated reaches along single streams. Streams within the wet tropics are more hydrologically active than comparable temperate streams with regard to stream power and flood durations and frequencies, and tropical streams generally are more variable seasonally and between years (Haines *et al.* 1988, McMahon *et al.* 1992). The response of streams to these very different hydrological regimes is mostly poorly understood and theories established in temperate regions are frequently used to explain tropical phenomena, without any sound basis. Pearson (1999) provided an overview of the effect of vegetation in the wet tropics region of north-eastern Queensland and Amos *et al.* (2004) discussed the erosional effects of extreme variable discharges of the Burdekin River in the wet-dry tropical region of north-eastern Queensland. However, there are few other published examples of erosion in north-eastern Queensland tropical systems, and no published research on the fine-scale effect of tree roots on erosion rates in the region. Vegetation is commonly used as a bank stabilisation strategy, despite the lack of quantitative data supporting its use. The investigations to be reported here will add important case studies to the existing knowledge base, and will contribute to theories of streambank retreat and stability.

Most studies in this region have been descriptive manuals or technical reports concentrating on broad catchment-scale processes (e.g. Australian Water Allocation Management Plans) or are general erosion/bank stability studies (e.g. Kapitzke *et al.* 1995, Pearson 1999) and do not discuss specific bank retreat rates. The lack of data on bank retreat rates makes it difficult to provide appropriate input to land management strategies and limits comparability of bank retreat rates between geographic regions. Hence, despite considerable anecdotal evidence suggesting fast-moving streams in north-eastern Queensland, there is little research to support this. For example, Ian Drummond & Associates Pty. Ltd. (1993) discuss 'extensive erosion' (> 4000 m of erosion in the lower 67 km of Tully River) and the slowing of erosion rates in the Tully River, but no rates are recorded. Kapitzke *et al.* (1995) and Sands and Kapitzke (1998) discuss detailed bank stability data collected from the Herbert River but similarly do not provide detailed data on bank retreat rates.

1.5.10 Literature summary

This review of the literature raises several issues relevant to measurements of bank retreat. Firstly, there is an argument for standardised methods of recording bank retreat rates. It is important that studies that deal with bank retreat rates include standardised units (e.g. bank retreat as a percentage of width) to enable comparisons between streams in different geographic and climatological regions.

Secondly, there is an argument for the adoption of standard methods of data collection to ensure accurate comparisons between reported bank retreat rates. Improvements in surveying techniques now provide excellent opportunity for the comparative measurement of bank retreat rates. Thirdly, there is the important issue of the influence of local conditions in determining bank retreat rates. Local bank conditions are potential key factors, especially the interactions between stream flow, stratigraphy and vegetation characteristics. These interactions are rarely considered together.

Finally, bank retreat is a process that has attracted worldwide research attention due to its often catastrophic nature; however, there is a dearth of research in some major geographic and climatological regions. This shortage of information needs to be addressed to improve local bank retreat knowledge and to enable appropriate local management options to be developed (Daniels and Rhoads 2003, Hudson and Kesel 2000, Nanson and Hickin 1986), as well as to enable a more robust general understanding of this important process.

1.6 Information gaps

Streambank erosion processes, rates, controls and effects have all received considerable attention, but several clear gaps remain in our knowledge of bank erosion globally. Knowledge gaps relevant to this study are:

- although there has been widespread research into root controls of erosion and bank stability, no published studies have focussed on direct interactions between RAR and fluvial processes at the bank-channel interface;
- streambank erosion processes and their causes in tropical regions in general, and north-eastern Queensland in particular, are poorly understood; this paucity is especially prevalent in the wet-dry tropical regions; and
- measurements of riparian root densities of tropical vegetation and their variation with depth are rare.

1.7 General aims and significance of project

A better understanding of bank erosion and retreat rates in the tropics is important due to its implications for local stream and land management issues and also for the potential to contribute to global understanding of bank retreat by addressing significant gaps in knowledge. Additionally, an understanding of erosion causes and factors or processes that slow or hasten scour and overall retreat rates can help provide guidelines for riparian monitoring and management. Thus, this thesis aims to improve our understanding of aspects of erosion of selected north-eastern Queensland streams (as examples of tropical systems), including:

- the rate at which these streams retreat;
- the differences in bank retreat rates between streams of the wet and wet-dry tropics;
- the differences in bank retreat rates and controls between tropical and temperate streams;

- the effect of various factors on retreat, including hydrological regime, root density and above-ground characteristics, stratigraphy and sedimentology and curvature;
- differences in erosion at different bank depths; and
- the effect of variations in vegetative, hydrological and geomorphological erosion factors on these erosion rates.

1.8 Thesis overview

Chapter 2 describes the selection of the study streams, reaches and sites. It outlines their location and their climatological, hydrological, geomorphological and geological setting and their general vegetative characteristics.

Chapter 3 examines the rates of bank retreat and erosion observed in the selected study streams, providing comparisons between the wet and wet-dry tropics hydrological regimes and also with global data. The differences in hydrology between the streams and the disparities in magnitude of the wet season of the different streams are analysed, and the effect of erosion mechanism on rates of bank retreat is tested.

Chapter 4 investigates the driving forces behind bank retreat in the three study streams, focussing on the influences of vegetation, sedimentology and stratigraphy.

Chapter 5 examines the depth-related variations in root area ratio (RAR), the limitations to rooting depth and spread within the banks of the three study streams, and the influence of RAR and other scour driving forces on rates of scour at different depths.

Chapter 6 summarises the findings, provides suggestions for future research and assesses the significance of the results of the project with respect to management implications.

CHAPTER 2
STUDY SITES

2.1 Wet and wet-dry tropics regions of north-eastern Queensland

The terms wet tropics and wet-dry tropics refer to two regions of north-eastern Queensland that have different climates and streams that experience different hydrological regimes (McMahon *et al.* 1992). The wet tropics region includes all catchments north from Ingham (lower Herbert River catchment) to the Daintree catchment (McDonald and Weston 2004) (Figure 2.1). It is an area characterised by high rainfall ($\overline{x} > 1500$ mm a^{-1}) with considerable spatial, seasonal and inter-annual variation (McDonald and Weston 2004). Stream discharges reflect this precipitation variability (Table 2.1), but are characterised by perennial flows. The wet-dry tropics region (Neil *et al.* 2002) is also referred to as the seasonally wet tropics (Ebisemiju 1994, Gupta 1995) and dry tropics (Kapitzke *et al.* 1996). The term wet-dry tropics is used in this thesis as it clearly describes the two contrasting seasons (wet and dry) experienced within the region. In north-eastern Queensland, the wet-dry tropics includes the Black, Ross, Haughton, Don and Burdekin River catchments (Figure 2.1). These catchments generally experience much lower annual average precipitation than the wet tropics (640 – 1510 mm a^{-1}) and precipitation is more variable spatially, seasonally and from year to year. Most catchments within this region receive the majority of their rainfall during the wet season (December-April), and many receive little to no rainfall during the dry season months (May-November) (Clewett *et al.* 2003). The stream hydrology reflects the precipitation variation (Table 2.2), with many streams ceasing to flow in the dry season, particularly small lower-order streams with smaller catchments to sustain baseflow.

2.2 Identification of statistically different wet and wet-dry tropics regions

A Multiple Response Permutation Procedure (MRPP) in the PC-ORD package (McCune and Mefford 1999) was used to determine whether hydrological characteristics of wet and wet-dry tropics streams differed significantly. This was performed to enable even ungauged streams to be identified as wet or wet-dry tropical on geographic location alone. All gauged streams in the catchments in Figure 2.1 were used in the analysis. MRPP acts as a Multivariate Analysis of Variance (MANOVA) but does not have the strict assumptions of multivariate normality and homogeneity of variances of the MANOVA. Hydrological characteristics included total discharge/catchment area (D/CA), seasonal variation (coefficient of variation – SCV), inter-annual variation (coefficient of variation – IACV) and wet season contribution to overall

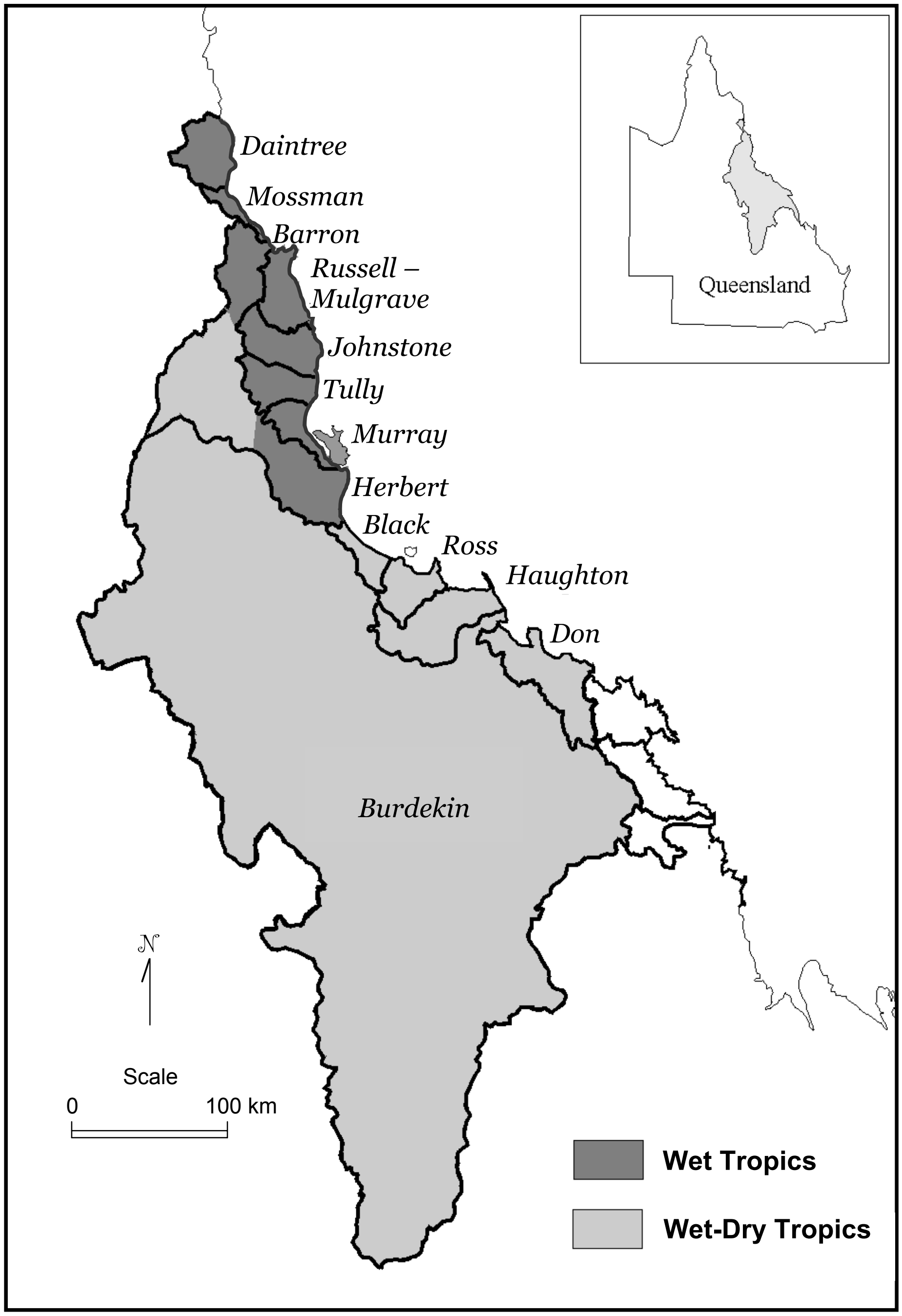


Figure 2.1 – Location of the wet and wet-dry tropics of north-eastern Queensland, with major river catchments indicated.

Table 2.1 – Precipitation and discharge variability within selected stream catchments of the wet tropics region of north-eastern Queensland, showing the similar traits between precipitation and discharge.

Data from Queensland Department of Natural Resources and Mines and Clewett *et al.* (2003).

Catchment*	Precipitation			Discharge		
	Mean annual (mm)	Inter-annual CV (%)	Seasonal CV (%)	Mean annual/area (ML/km^2)	Inter-annual CV (%)	Seasonal CV (%)
Babinda Creek	4246	25	72	4409	29	72
Behana Creek	1990	33	100	2096	41	91
Liverpool Creek	3595	24	70	1989	42	79
Mossman River	2377	28	93	2834	33	71
N. Johnstone	3595	24	70	1880	35	74
Tully River	4040	25	72	2048	39	64

* Babinda and Behana Creeks are in the Russell-Mulgrave catchment; Liverpool Creek is in the Johnstone catchment

Table 2.2 – Precipitation and discharge variability within selected stream catchments of the wet-dry tropics region of north-eastern Queensland, showing the similar variability of precipitation and discharge.

Data from Queensland Department of Natural Resources and Mines and Clewett *et al.* (2003).

Catchment*	Precipitation			Discharge		
	Mean annual (mm)	Inter-annual CV (%)	Seasonal CV (%)	Mean annual/area (ML/km^2)	Inter-annual CV (%)	Seasonal CV (%)
Black River	1146	42	108	318	120	138
Bohle River	1141	39	107	350	117	137
Bowen River	720	39	86	112	124	111
Clarke River	676	42	102	140	120	150
Haughton River	1166	44	104	212	85	155
Ross River	1141	39	107	167	185	142

* Bohle River is between the Ross and Black catchments; Bowen and Clarke Rivers are in the Burdekin catchment

discharge (WSC), data being derived from the Queensland Department of Natural Resources and Mines and Clewett *et al.* (2003). A Principle Components Analysis (PCA) was also used to graphically represent the differences on the basis of the same variables.

The two procedures showed clear statistical differences between streams of the wet and wet-dry tropics. The MRPP identified that the two groups (wet and wet-dry tropics) were significantly different according to their hydrological characteristics ($T = -34.92$, $A = 0.29$, $p < 0.001$), with heterogeneity within groups being less than expected. The PCA identified similar distinct groupings of wet and wet-dry tropics streams according to those characteristics, with little overlap existing between groups along Axis 1 of the PCA (Figure 2.2). However, some variability existed within the two hydrological regimes with regard to the percentage of wet season discharge and the SCV, as shown by regressions of these variables with both axes (Figure 2.2). Overlap also existed between the two groups with regard to D/CA and IACV.

However, the regressions between these two variables and Axis 1 (Figure 2.2) showed that sites within the wet and wet-dry tropics showed clear demarcation with regard to hydrological characteristics. Thus, where gauge data are unavailable or the dataset is of insufficient length or quality, ungauged streams in the north-eastern Queensland region can safely be assigned to either the wet or wet-dry tropics according to (1) their geographic location and (2) the hydrological characteristics of surrounding catchments.

2.3 Selection of study streams and reaches

Selection of study streams, reaches and sites in the two study regions addressed the following criteria:

- ease of access;
- comparable dimensions;
- similar locations in catchments;
- availability of climatological and hydrological data; and
- presence of both vegetated and unvegetated sections along the streams.

Selection of streams with downstream floodplain reaches in agricultural areas ensured few accessibility limitations. Selection of floodplain reaches with comparable dimensions and location in catchments also ensured that no scale bias was introduced in this study. Scale, with regard to catchment area, channel dimensions and associated hydrological parameters, is an important issue as differences in stream scale may cause considerable problems for direct comparisons of bank retreat rates between streams (Lawler 1993a) (Section 1.7.7).

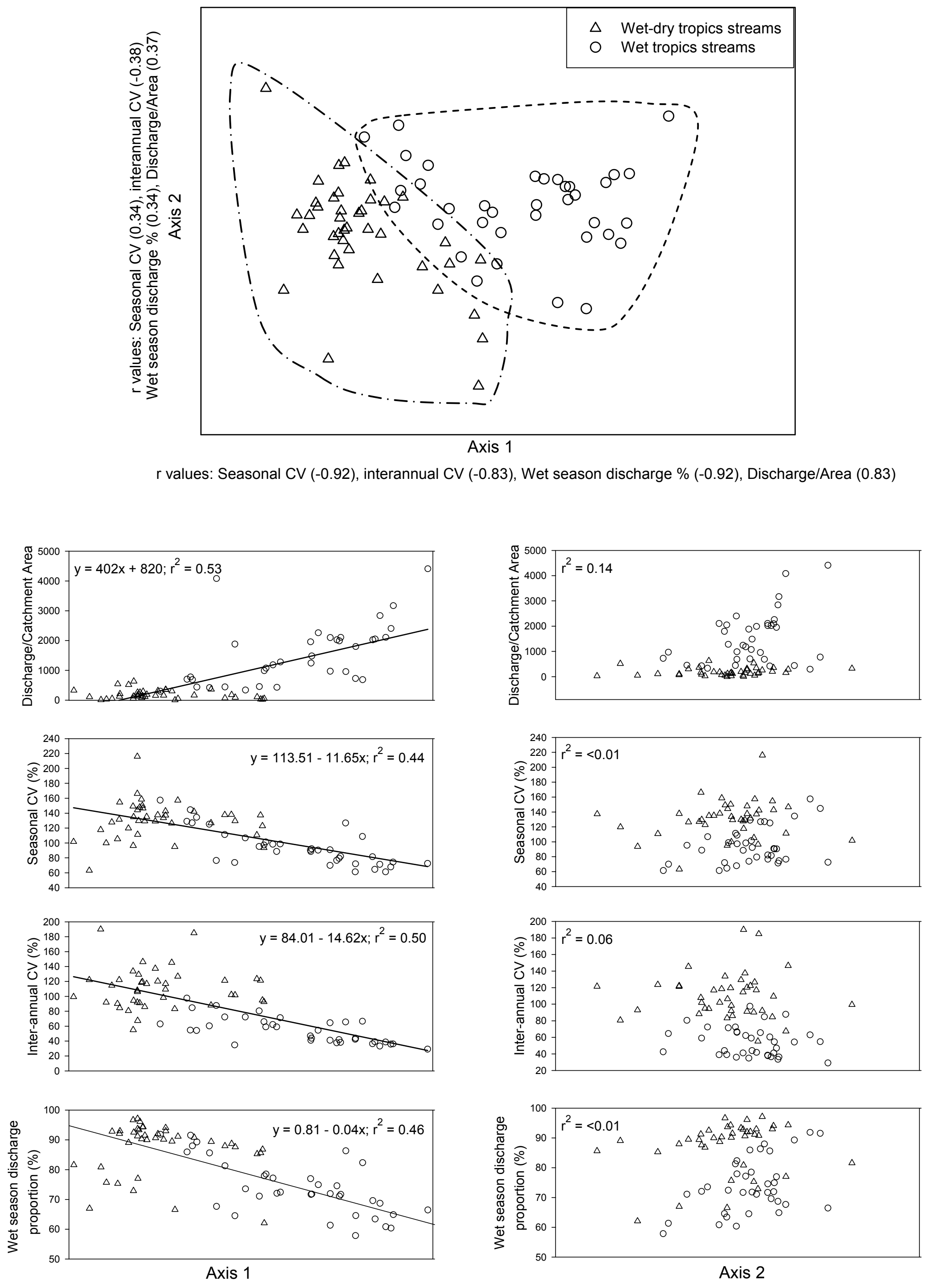


Figure 2.2 – Results of the PCA of hydrological characteristics of wet and wet-dry tropics streams.

Main plot shows PCA results, identifying the groupings of wet and wet-dry tropics streams. Correlation coefficients (r) of hydrological characteristics with each axis are shown along the axes of the main plot. The subplots show the results of regressions between the hydrological variables and each of the axes.

Long-term climatological data for each stream was a necessity for stream comparison, and the availability of hydrological data was preferred. However, adequate hydrological data was sparse for most of the suitable study streams. Contiguous vegetated and unvegetated reaches were essential to this study and this criterion constrained site selection, as few streams in north-eastern Queensland provided suitably vegetated streambanks.

Reaches on Jarra Creek, Liverpool Creek and Thornton Creek conformed to these site selection criteria better than other comparable streams. They all had easily accessible downstream reaches which allowed regular site visitation and had similar dimensions, minimising the possibility of scale bias. All streams drained small catchment areas (99-310 km^2) and ANOVA of bankfull width data from this study and from previous studies of Jarra Creek (Pearson 1999) and Liverpool Creek (Greenslade 2001, Jack 2001) showed no significant difference in width between the three streams ($F_{2,164} = 0.153$, $p = 0.859$). The three study streams were also examples of the very few accessible streams that provided sufficient reaches of both vegetated and unvegetated streambanks. Descriptions of the three study streams are provided below.

2.3.1 Jarra Creek

Location and Description

Jarra Creek is a tributary of the Tully River and is located approximately 200 km north of Townsville in north-eastern Queensland (Figures 2.3 and 2.4). Its catchment is wholly within the wet tropics – its headwaters rise at over 800 m and are situated in the Walter Hill Range approximately 25 km north-east of the Tully township. Jarra Creek flows in a south-easterly direction, is 73 km long and its sub-catchment has an area of 99 km^2.

Climate and hydrology

Jarra Creek is situated in one of the wettest parts of Australia (Lait *et al.* 1996), receiving between 2700 (Koombooloomba Dam gauge) and 4800 mm per annum (Walter Hill Ranges). It experiences large inter-annual (CV = 25%) and seasonal variations in rainfall (CV = 72%) (Clewett *et al.* 2003, Johnson 1998, Water Resources Division 1995) (Figures 2.5 and 2.6). Seventy percent of the precipitation in the Jarra Creek region falls during the wet season (Johnson 1998). No hydrological data is available for Jarra Creek, but the hydrological regime of nearby Tully River (of which Jarra Creek is a tributary) reflects the rainfall patterns (inter-annual CV = 39%; intra-annual CV = 64%). As a tributary of Tully River, and with similar catchment characteristics, Jarra Creek would be expected to follow similar patterns. Both are perennial systems that show considerably stronger flows late in the wet season and, therefore, are affiliated to the global flow regimes 6 (mid-summer peak) or 9 (early autumn peak) identified by Haines *et al.* (1988).

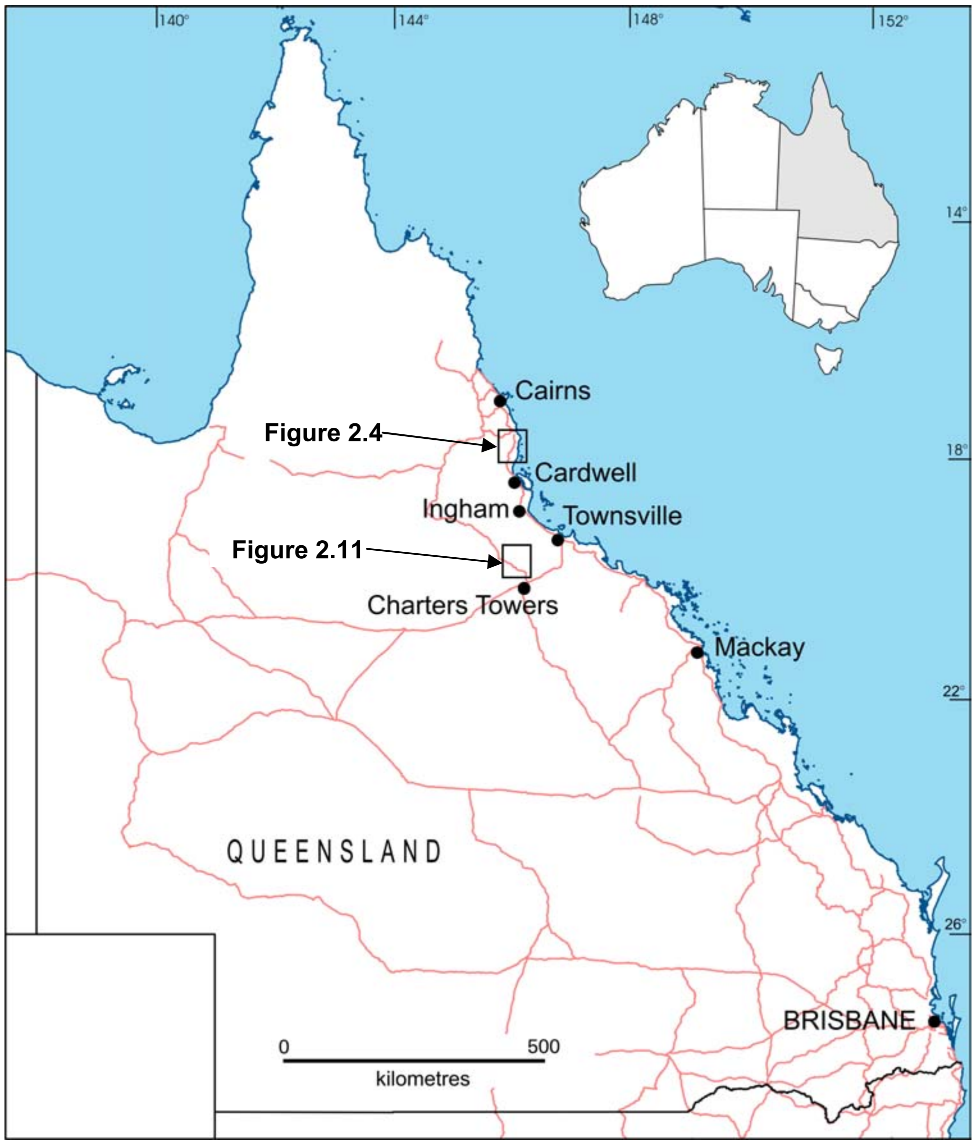


Figure 2.3 – Location of study areas in wet tropics (Figure 2.4 box) and wet-dry tropics (Figure 2.11 box).

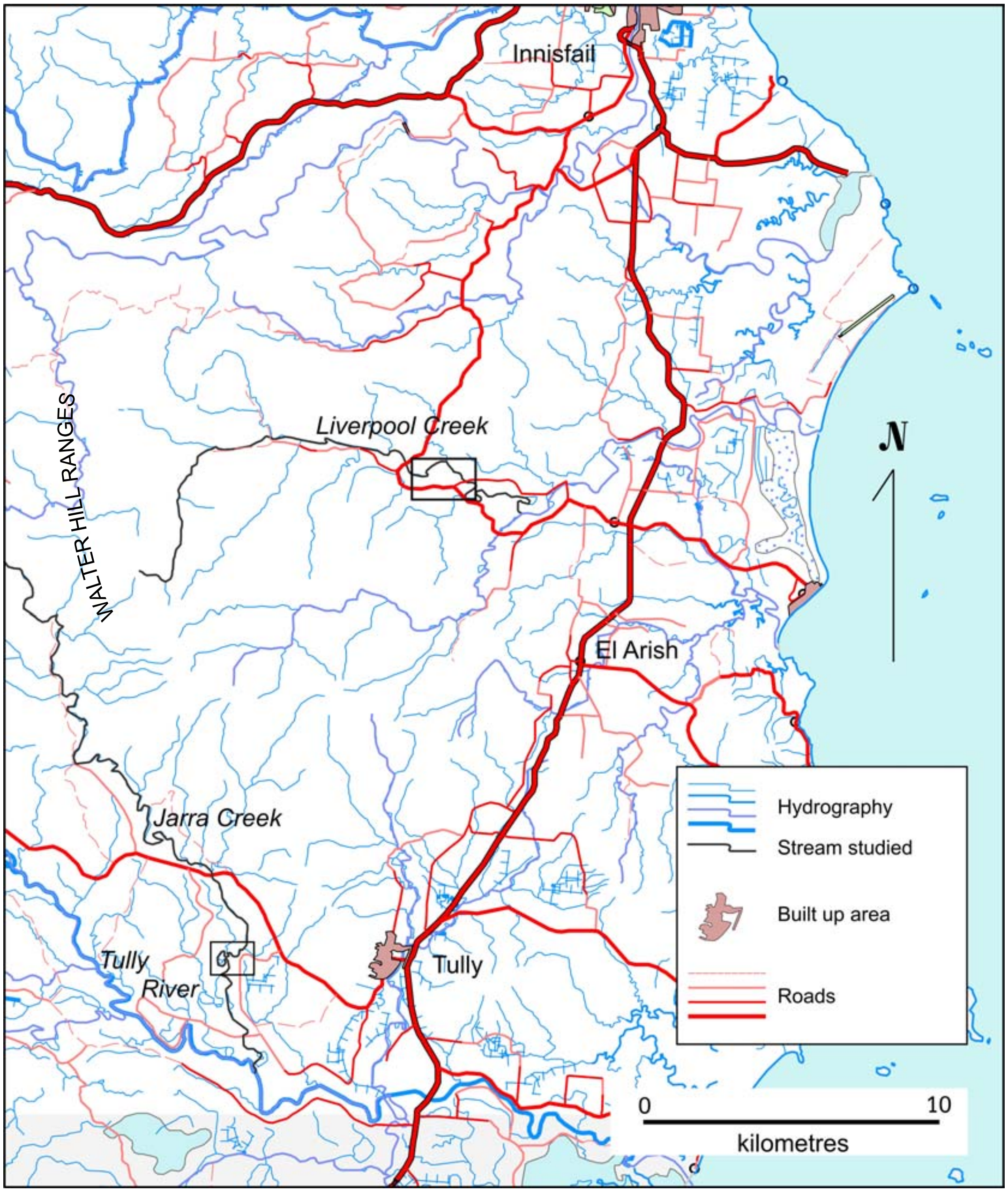


Figure 2.4 – Locations of wet tropics study reaches, indicated by boxes on Liverpool Creek and Jarra Creek.

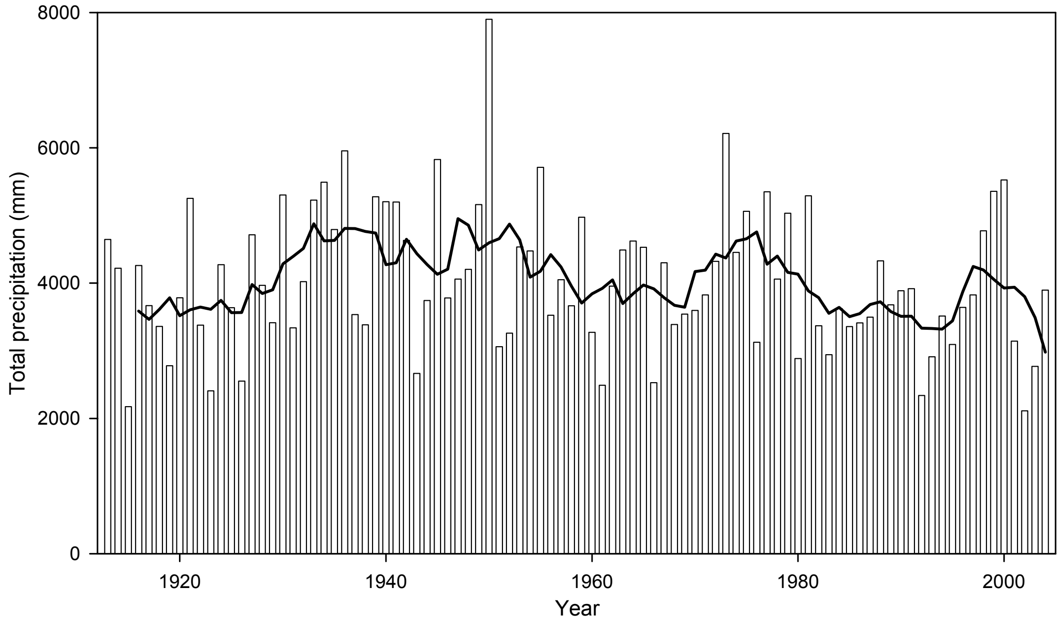


Figure 2.5 – Yearly precipitation totals for the Jarra Creek region. Line plot shows seven-year running mean.

Data compiled from Tully Sugar Mill records (17º15'S, 145º56'E) (Figure 2.4) (Clewett *et al.* 2003).

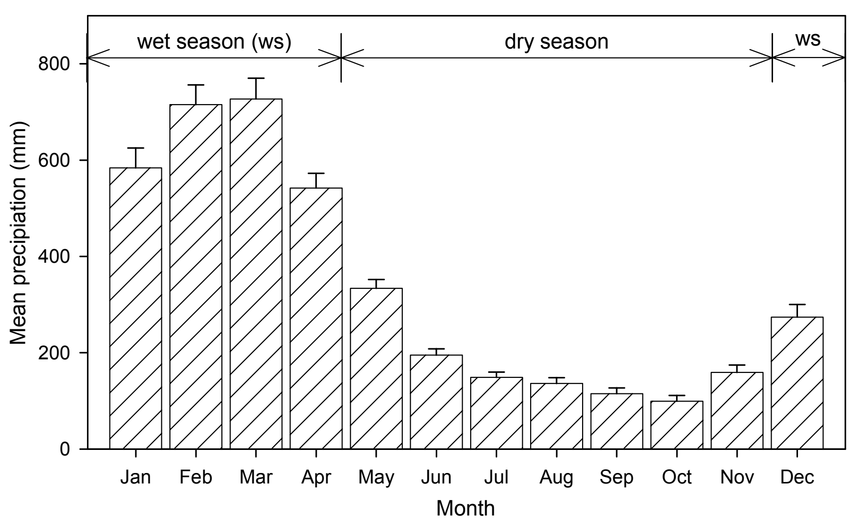


Figure 2.6 – Mean monthly rainfall data for the Jarra Creek region (1913–2006). Error bars represent standard error.

Data compiled from Tully Sugar Mill record (17º15'S, 145º56'E) (Figure 2.4) (Clewett *et al.* 2003).

Geology and Geomorphology

Jarra Creek has an extremely steep source zone (slope = 7.6º) and a narrow low-gradient floodplain (slope = 0.09º) (Figure 2.7). Its source zone flows through mountains largely composed of biotite-hornblende granite, adamellite and granodiorite, with small outcrops of quartz, while the floodplain stratigraphy is composed of highly stratified and cross-bedded Quaternary alluvial sediments of similar geological origin (Bureau of Mineral Resources 1964). General stratigraphic investigations of the region have identified three broad sedimentary units: an upper stratum consisting of mixed sand, silt and clay particles, most likely consisting of old overbank deposits from high magnitude flow events; a stratum consisting of coarse sand-gravel (sometimes with cobble) that is largely found below the mixed stratum, most probably consisting of incised old bed or bar material; and a third stratum normally found below the sand-gravel stratum with a far higher clay content (Figure 2.8) (Section 4.3.2). While these different sedimentary units normally occur in this order down the banks, there are also examples of homogeneous banks, consisting of only the sandy unit, and heterogeneous banks missing the lower clay unit.

The heterogeneous nature of floodplain sediments is partly responsible for the considerable variation in cross-sectional shape and size of Jarra Creek within the floodplain (mean channel width of 46.1 m, C.V. of 29% – Pearson 1999). The different sedimentary units that constitute the floodplain provide varying resistance to stream incision and bank retreat. The nature of floodplain sediments also appears to influence the Jarra Creek planform. Floodplain meander form varies between irregular wandering and regular/irregular meanders. Sinuosity varies accordingly (P = 1.2-2.8), reflecting spatial variations in sediment.

Vegetation and land use

Many landholders have left remnant patches of complex riparian vegetation that are interspersed with cleared reaches with only simple ground storey vegetation, providing suitable configuration for comparative studies between adjacent well-vegetated and poorly-vegetated banks. The remnant patches of riparian vegetation are largely mesophyll vine forest (Type 2a) dominated by the native trees *Elaeocarpus angustifolius* (blue quandong), *Polyscias elegans* (silver basswood), *Ficus variegata* (variegated fig), *Alstonia scholaris* (white cheesewood), and *Aleurites rockinghamensis* (candlenut) (Tracey 1982, Tracey and Webb 1975). Climbing palms (*Calamus australis* and *C. caryotoides*) are also common. These communities are dense, normally exceeding 20 individuals in a 10 × 10 m quadrat.

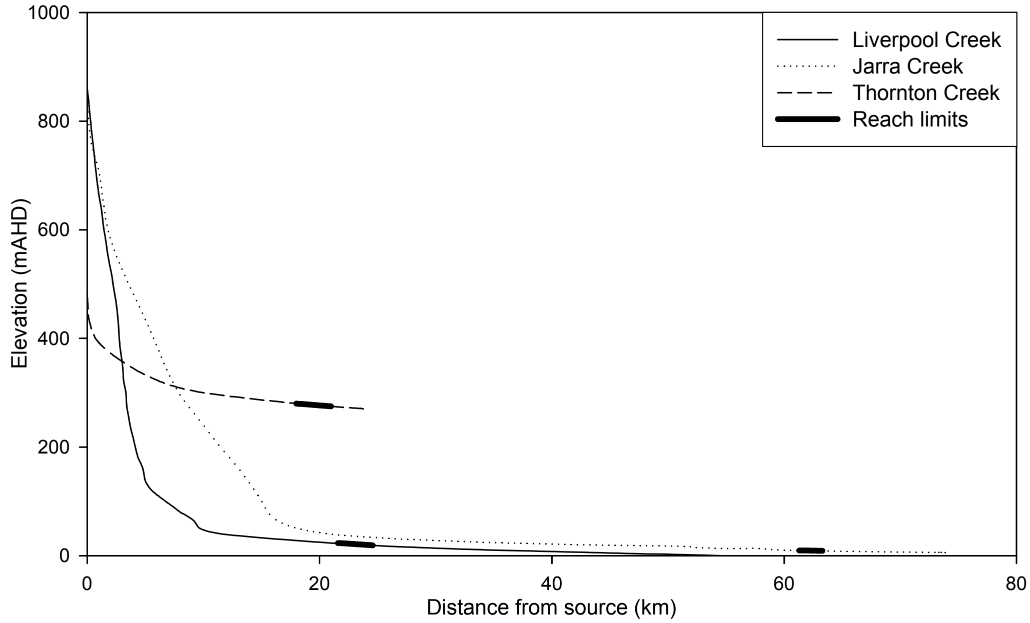


Figure 2.7 – Longitudinal profiles of the three study streams showing location and length of each study reach.

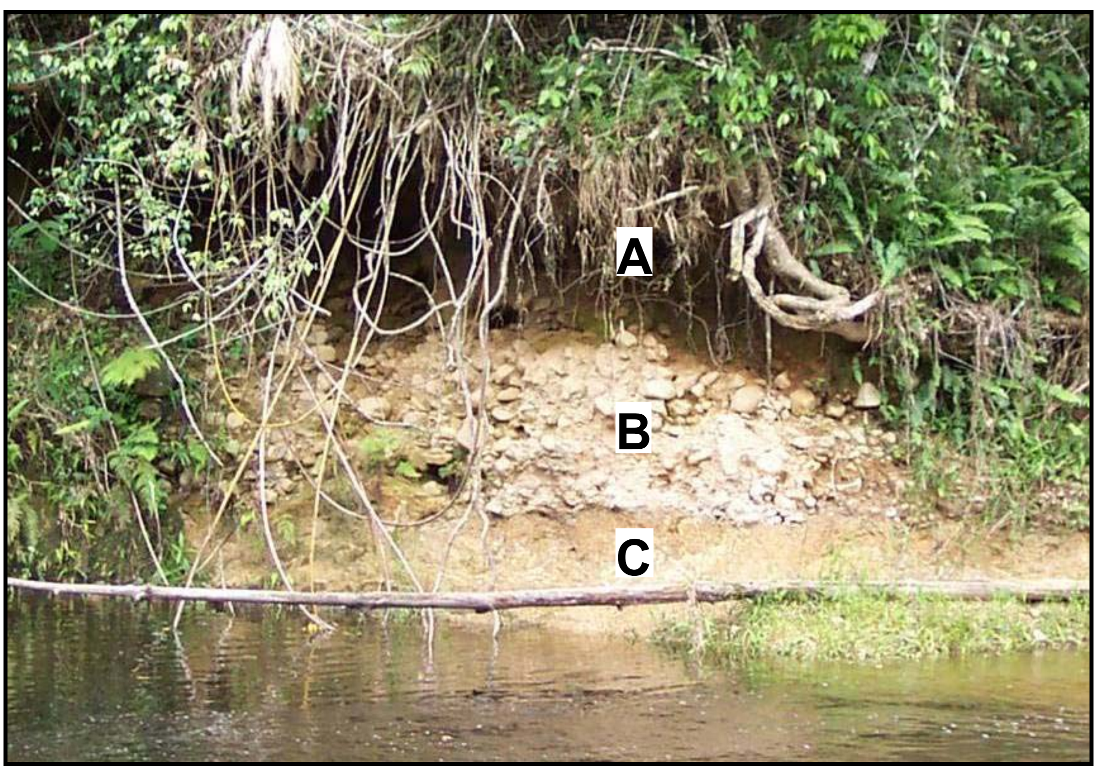


Figure 2.8 – Jarra Creek bank showing the three general sedimentary units present: (A) mixed sand-silt-clay stratum; (B) sandy-gravel stratum mixed with cobble; and (3) basal clayey stratum.

The large cleared stretches are inhabited by invasive exotic grass species, especially *Panicum maximum* (guinea grass), *Pennisetum purpureum* (elephant grass), *Brachiaria mutica* (para grass) and other introduced species, such as *Solanum mauritianum* (wild tobacco), *Stachytarpheta* spp. (snakeweeds) and *Rubus rosifolius* (wild raspberry).

Jarra Creek is one of the few remaining north-eastern Queensland streams with extensive reaches of relatively undisturbed native vegetation remaining on its floodplain (Pearson 1999). Forty percent of its stream length is in very good condition (Johnson 1998) and, as such, it has been the focus of several studies (Burrows and Butler 1999, Lait 2003, Werren 1999). This previous work provides a useful context and background information for this study.

2.3.2 Liverpool Creek

Location and Description

The Liverpool Creek catchment is located approximately 200 km north of Townsville (Figures 2.3 and 2.4) and is situated between the Johnstone and Tully River catchments (shown in Figure 2.1), in the wet tropics. It drains approximately 311 km^2 and flows for approximately 50 km eastwards from its headwaters in the Walter Hill Range to its mouth.

Climate and hydrology

The Liverpool Creek region receives between 3500 and 4800 mm of rainfall per year ($\bar{x}$ = 3595 at Innisfail gauge: 17º31'S, 146º02'E), with 71% falling within the wet season (December-April) (Clewett *et al.* 2003). Thus, there is considerable inter- (CV = 24%) and intra-annual (CV = 70%) variation (Figures 2.9 and 2.10). The hydrology of Liverpool Creek reflects the climate, with similar inter-annual (42%) and seasonal variations (79%). A stream gauge (Queensland Department of Natural Resources and Mines (DNRM) gauge number 112102A, located 39 km upstream from the mouth at location 17º42'S, 145º54'E) shows Liverpool Creek to be a perennial stream, subject to bankfull flows at the gauge position about once every 4 years – but experiencing flows up to 90% capacity once every 2.33 years (data source: DNRM, 2004). Its perennial nature and characteristic strong late wet season flows are a feature of global flow regime groups 6 (mid-summer peak) or 9 (early autumn peak) (Haines *et al.* 1988).

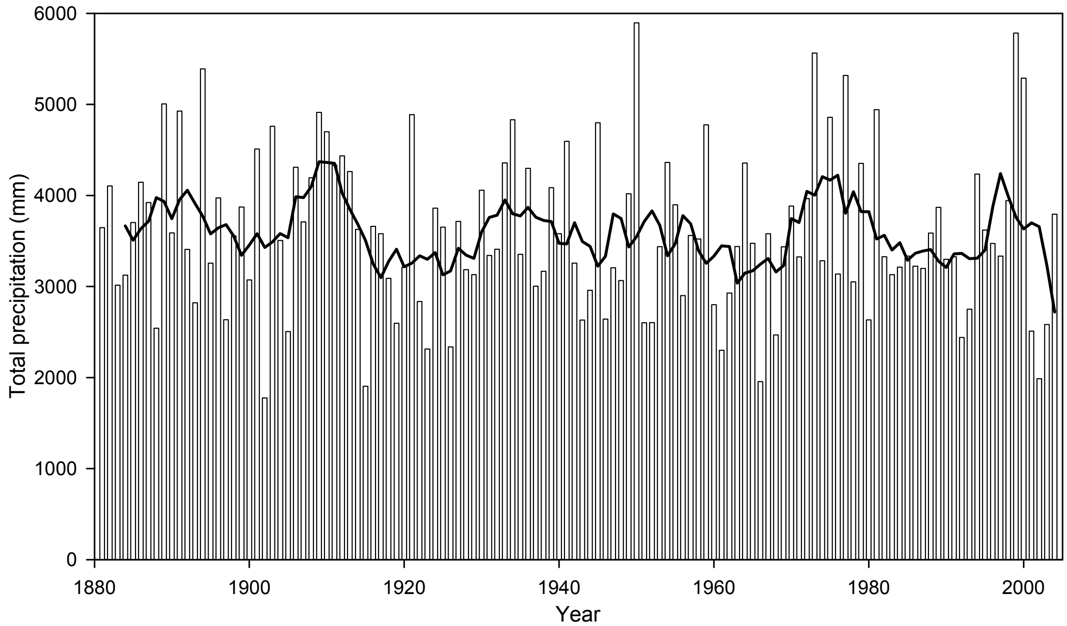


Figure 2.9 – Yearly precipitation totals for the Liverpool Creek region. Line plot shows seven year running mean.

Data compiled from Innisfail records (17º31'S, 146º02'E) (Figure 2.4) (Clewett *et al.* 2003).

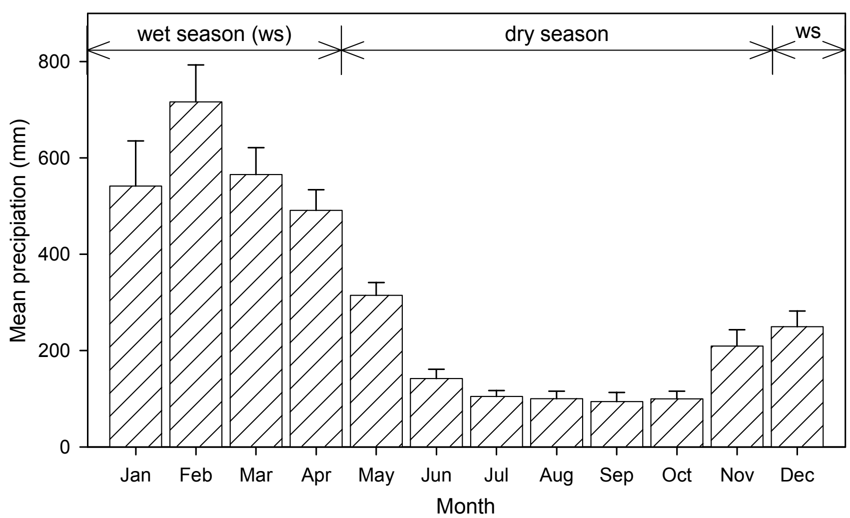


Figure 2.10 – Mean monthly rainfall data for the Liverpool Creek region (1972–2006). Error bars represent standard error.

Data compiled from El Arish Post Office records (17º49'S, 146º00'E) (Figure 2.4) (data source: Bureau of Meteorology, 2005).

Geology and Geomorphology

The headwaters of Liverpool Creek are situated in the Walter Hill Range. They are very steep (9.2º) and flow through mountains largely composed of Herbert River granite (adamellite) and low-grade Barron River metamorphics, including phyllite, slate, sericite schist and greywacke. The floodplain reach largely consists of a gradually-sloped (0.05º) meandering channel flowing through three alluvial sedimentary units similar to those in the Jarra Creek sub-catchment. Floodplain meander form is variable – from irregular wandering meanders (low sinuosity) in the upper extent of the floodplain to regular/irregular meanders (high sinuosity) in the mid- and downstream floodplain reaches. Figure 2.7 illustrates the longitudinal profile and slope of the main Liverpool Creek channel.

Liverpool Creek exhibits large variations in cross-sectional shape and size reflecting the large variations in sediment types adjacent to the channel. Forty cross-sections conducted along the length of the Liverpool Creek floodplain indicate an average channel width of about 48 m and a coefficient of variation of 31% (Greenslade 2001, Jack 2001).

Vegetation and land use

There are small communities of mesophyll vine forest (Type 2a) that are intersected by the stream (Tracey 1982, Tracey and Webb 1975). This forest is largely dominated by the native trees *Aleurites rockinghamensis*, *Callitris intratropica* (northern cypress), *Elaeocarpus angustifolius*, *Calamus australis* and *C. caryotoides*. These communities are dense, normally exceeding 20 individuals in a 10 × 10 m quadrat. However, most of the floodplain reaches of Liverpool Creek flow through sugar cane and banana farms. As a result, the majority of the floodplain is devoid of complex vegetation – the exotic grass species *Panicum maximum* and *Pennisetum purpureum* are the predominant bank vegetation, while the grass *Brachiaria mutica* inhabits sand bars and parts of the bed. The bed and banks of Liverpool Creek are also inhabited by other exotic species, including *Hymenachne amplexicaulis*, *Stachytarpheta* spp. and *Rubus rosifolius*.

2.3.3 Thornton Creek

Location and description

Thornton Creek is located in the wet-dry tropics approximately 73 km south-west of Townsville. It is 30 km long and drains a catchment of approximately 110 km^2. It is a tributary of Keelbottom Creek, which is a tributary of the Burdekin River (Figures 2.3 and 2.11).

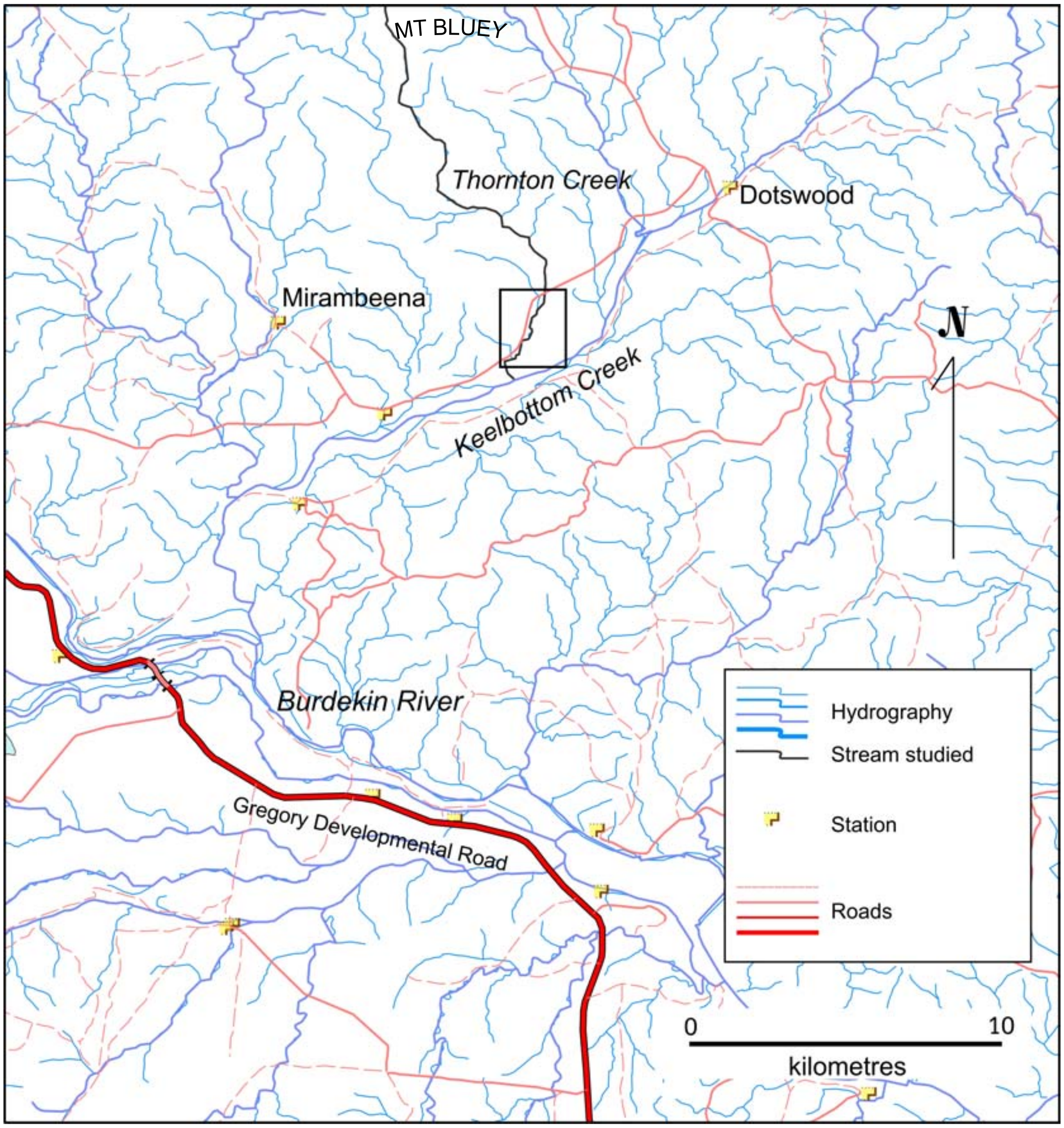


Figure 2.11 – Location of the Thornton Creek (wet-dry tropics) study reach, indicated by the box.

Climate and hydrology

The long-term gauges positioned at nearby Dotswood and Mirambeena Stations (Figure 2.11) show that Thornton Creek is located in the seasonally wet-dry tropics, its rainfall being low (~ 564 mm), and experiencing high seasonality, with 79% of the rainfall falling in the wet season (December-April) (Figure 2.12). The dry season is often devoid of rainfall (Rogers *et al.* 1999). The Thornton Creek catchment also experiences very high inter-annual variation in precipitation (CV = 39%). Figure 2.13 shows the variations in annual precipitation values at the two recording stations for each recorded year.

The hydrology of Thornton Creek reflects the variability in precipitation. Data obtained for the hydrology of Thornton Creek is only for a short period, but it still indicates considerable variation between the flow occurring in the wet and dry seasons, like surrounding catchments with longer collection periods (Figure 2.14). Thornton Creek is an intermittent stream – wet season flows are generally a response to rainfall events late in the wet season and dry season flows are infrequent or absent. The stream conforms to global flow regime group 7 (extreme late summer peak) (Haines *et al.* 1988).

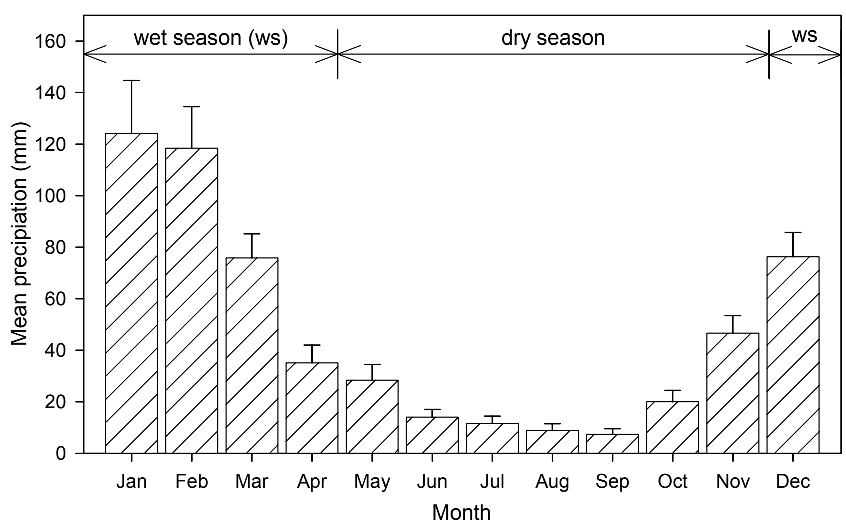


Figure 2.12 – Mean monthly rainfall data for the Thornton Creek region (1962–2006). Error bars represent standard error.

Data compiled from Mirambeena Station records (19º41'S, 146º07'E) (Figure 2.11) (data source: Bureau of Meteorology, 2005).

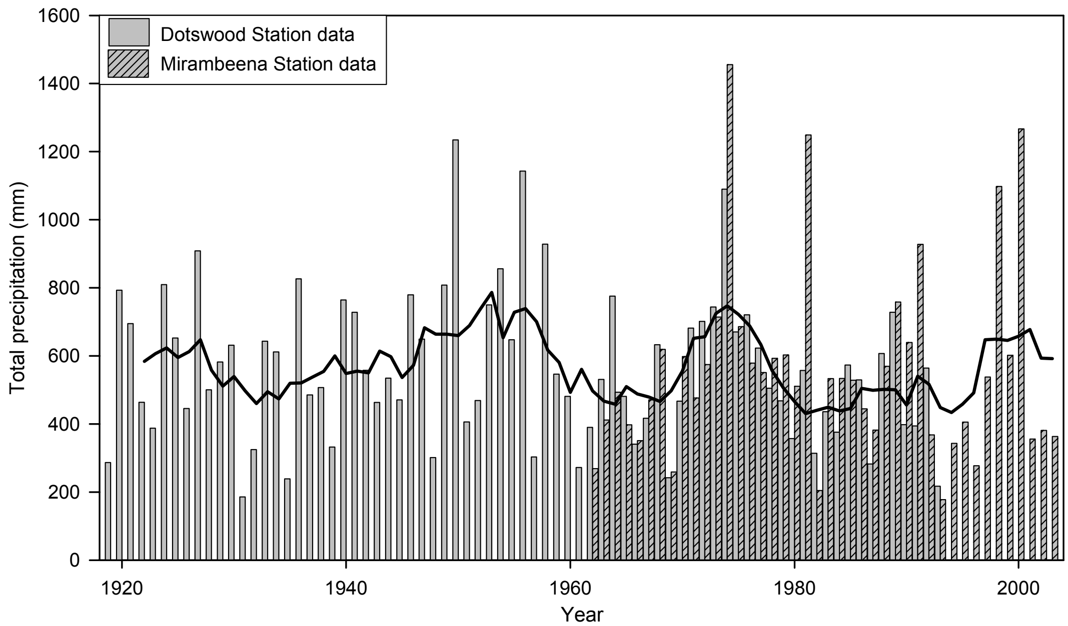


Figure 2.13 – Yearly precipitation totals for the Thornton Creek region. Line plot shows seven year running mean.

Data compiled from Dotswood Station (19°38'S, 146°17'E) and Mirambeena Station (19º41'S, 146º07'E) records (Figure 2.11) (data source: Bureau of Meteorology, 2005).

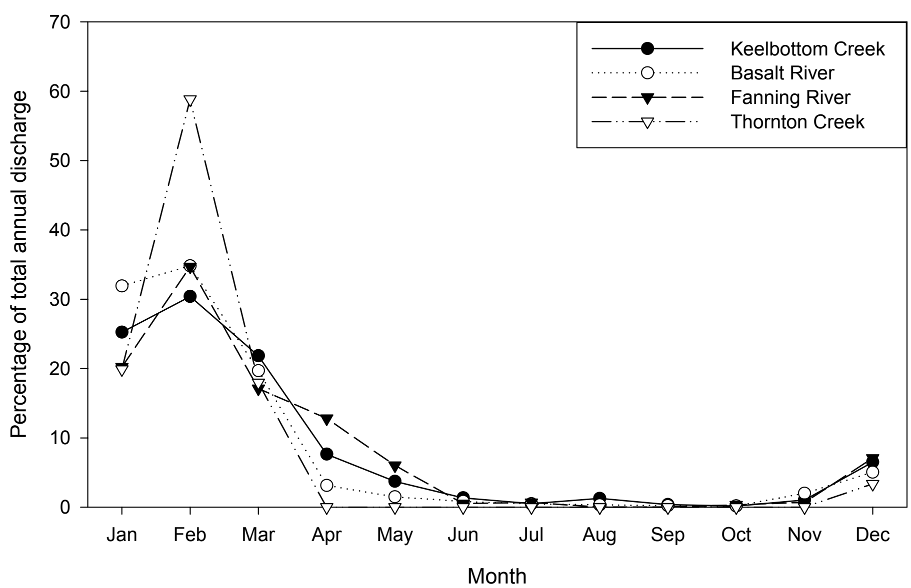


Figure 2.14 – Monthly discharge patterns (as a proportion of annual discharge) of Thornton Creek and nearby streams.

Geology and Geomorphology

Thornton Creek is shorter than the wet tropics study streams and has a smaller catchment area than Liverpool Creek; however, it has a similarly steep source zone (3.6º) and low gradient floodplain (0.12º) (Figure 2.7). Its headwaters originate from Mount Bluey (545 m), approximately 18 km north-west of the Dotswood Station and flow through three different geological formations – Piccadilly Formation (Ca: feldspathic sandstone, quartz pebble, conglomerate); lateritic Campaspe beds (Tl); and Pall Mall Adamellite (C-Pa: porphyritic biotite adamellite intruding older sandstone, siltstone and shale formations) (Bureau of Mineral Resources 1968). The Thornton Creek study reach flows through three main floodplain sedimentary units – a fine, very hard clay; coarse sand; and coarse sand interspersed with large stones.

The majority of the floodplain reaches are only mildly sinuous (P = 1.4) and consist of irregular wandering meanders. Sinuosity increases (P = 2.0) within five kilometres of its confluence with Keelbottom Creek. Meanders become more regular, with the occurrence of simple symmetrical, simple asymmetrical and compound asymmetrical meander loops (see Brice 1974).

Vegetation and land use

The floodplain vegetation consists of tall open woodland largely dominated by *Corymbia tesselaris*, *Eucalyptus brownii*, *E. clarksoniana* and *E. shirleyi*. The upper bank vegetation along the study reach includes the same species, while the lower banks and channel bed are vegetated by *E. camaldulensis* var. *obtusa*, *Melaleuca argentea* and *M. leucadendra*. Bank vegetation is generally sparse (< 15 trees/10 × 10 m quadrat) and bed vegetation comprises only scattered individuals.

Floodplain ground cover consists largely of mid-high to tall tussock and hummock grasses, rarely exceeding 1.0 m in height. Ground cover is mid-dense (McDonald *et al.* 1990) and is dominated by *Chrysopogon fallax* (ribbon grass) and *Heteropogon contortus* (black speargrass). Other major species present are *Urochloa panicoides* (liverseed grass), *U. mosambicensis* (Sabi grass), *Dichanthium sericium* (Queensland bluegrass), *Bothriochloa ewartiana* (desert Mitchell), *B. decipiens* (pitted bluegrass) and *Stylosanthes hamata* (Caribbean stylo). The banks along the study reach are occupied by similar species but have higher ground cover (closed/dense) (McDonald *et al.* 1990).

There are two main land uses that potentially influence the nature of the stream system. Grazing occurs on the Thornton Creek floodplain downstream of the Mirambeena Access Road off Mingela Road. The area upstream of the road has been crown land since 1988 and is managed by Department of Defence (Australia 1996, Rogers *et al.* 1999). This area was used for grazing until 2000. Since the expiration of leases, grazing pressure has been markedly reduced; however, limited rotational grazing still continues (Burrows *et al.* 2000).

Significance

While the Thornton Creek catchment has little human development within it, the importance of its health and stability is recognised by all stakeholders. Its health is important for sustainable use by the Department of Defence and graziers, as recognised by the considerable work conducted in the catchment and surrounding areas (e.g. Burrows 1999a, 1999b, Burrows and Tait 1999, Butler *et al.* 1997, Rogers *et al.* 1999). The majority of this research has been funded by the Department of Defence to ensure sustainable management, indicating the importance placed on the catchment.

2.4 Selection of study reaches and sites

To meet the requirements of the aims (Section 1.7), study reaches were selected to ensure adequate representation of vegetated and non-vegetated banks in close proximity to each other, and on relatively flat floodplains, to remove the effects of discharge, stream size and slope. Reaches containing few tributary confluences were chosen to minimise the effect of extra discharge entering the system. Selection of reaches was also determined by availability of vehicular access to the stream.

The study reach on Jarra Creek was approximately 2 km long, starting 100 m downstream of a ford accessible from Syndicate Road, about 5 km downstream from the Cardstone Road Bridge. It ended 10 km upstream from the Jarra Creek–Tully River confluence. Figure 2.4 shows the reach location relative to the stream length. No tributaries entered the creek within the study reach.

The study reach on Liverpool Creek was located approximately 1.5 km downstream of the Innisfail–Japoon Road crossing and extended 3 km downstream to the Walter Lever Estate Road bridge crossing. Figure 2.4 shows the reach location relative to the stream length. A small fourth-order tributary with a drainage area of 12 km^2 entered the stream within the study reach, but was expected to have minimal effect on overall discharge in the reach (representing only about 4% of the catchment).

The Thornton Creek study reach began about 6 km upstream from the Thornton Creek–Keelbottom Creek confluence (100 m downstream of the Mirambeena Access Road) and flowed for 3.5 km through a floodplain largely occupied by grazing land and Commonwealth Defence Force land. No major tributaries entered Thornton Creek within the study reach.

Within each study reach, study sites were all located on meander bends to ensure that the curvature/sinuosity effect was minimised. Ten sites were chosen in each of Jarra Creek and Liverpool Creek. Fourteen sites were chosen on Thornton Creek because its reach was longer and more sites were needed to provide greater representation of the wet-dry tropics. Figures 2.15, 2.16 and 2.17 show the location of the study sites in the three study reaches.

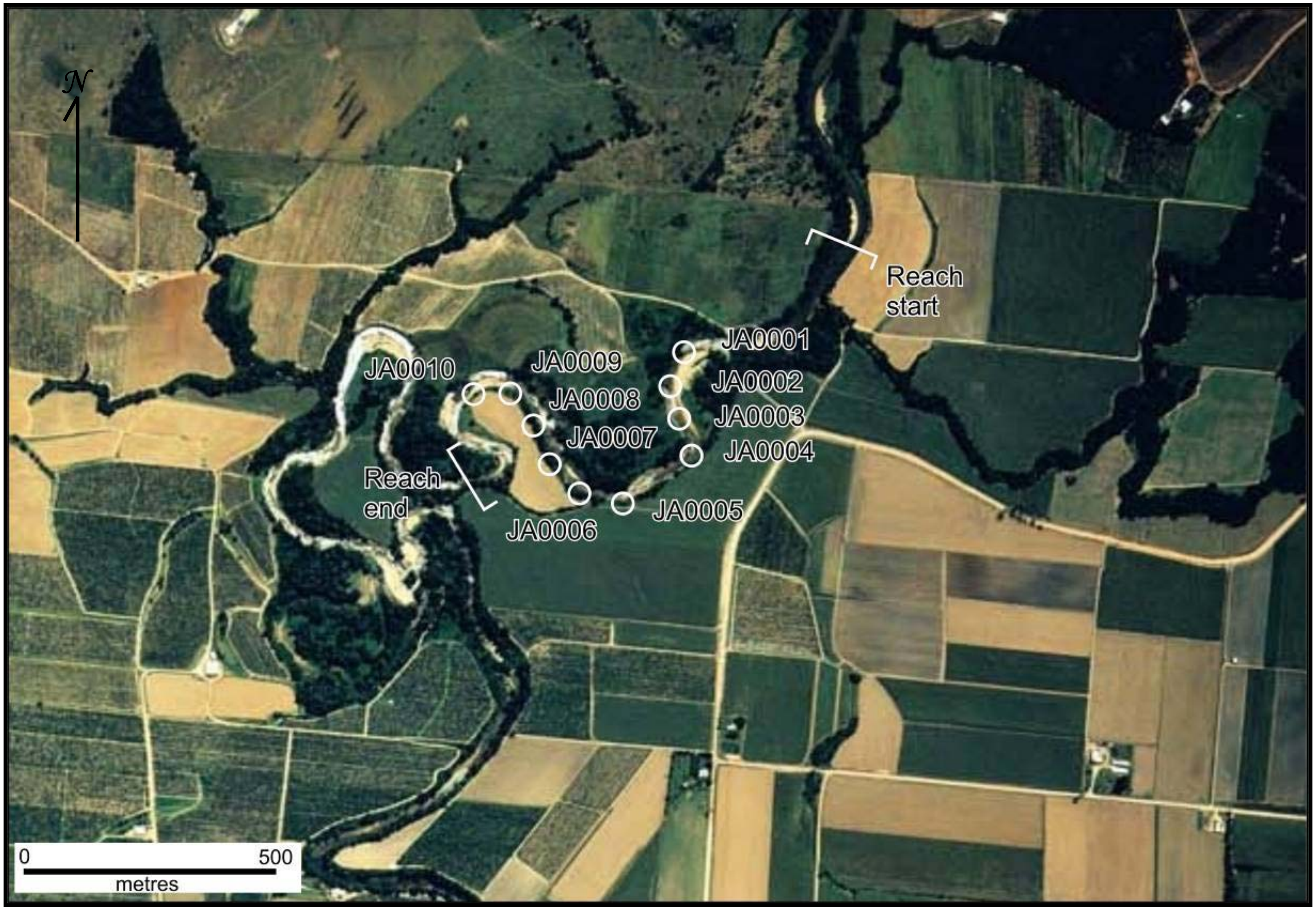


Figure 2.15 – Study site locations in the Jarra Creek reach identified in Figure 2.4.

Figure 2.16 – Study site locations in Liverpool Creek reach identified in Figure 2.4.

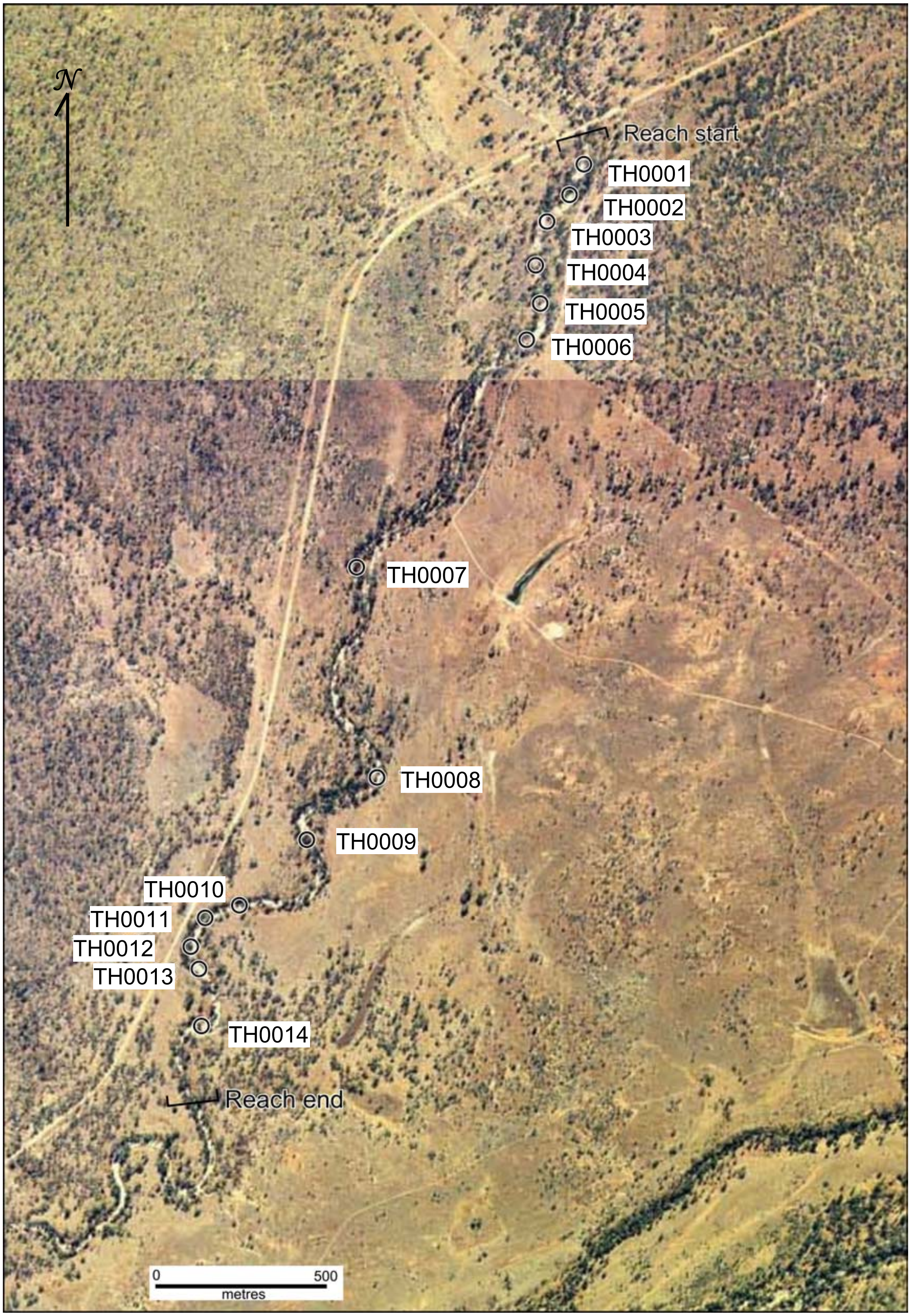


Figure 2.17 – Study site locations in Thornton Creek reach identified in Figure 2.11.

CHAPTER 3
BANK RETREAT RATES AND MECHANISMS

3.1 Introduction

Bank retreat occurs when the stresses generated by flowing water and local bank characteristics exceed the resistance provided by the bank. Section 1.5 discusses this interaction and notes that it is largely a function of various locally and regionally controlled environmental factors that act in concert to determine the mechanism and rate of retreat. These factors include climate, discharge, slope, bank material and structure, bank geometry, bank vegetation and curvature. It is important to understand these interactions as they have implications for resource management.

Section 1.5.2 showed that climate influences bank retreat rates because of the influence of precipitation quantity, intensity and duration on stream hydrology and, therefore, on erosion driving forces. On average, streambanks in wetter climates retreat faster. However, within any climatic region, there is significant local variation in bank retreat due to variations in erosion driving forces. The tropics are no exception – for example, stable banks that undergo minimal retreat have been observed in several tropical systems (e.g. Bishop 1987, Okagbue and Abam 1986).

In the Australian tropics, hydrological and geomorphological variations between systems are often poorly understood. In the wet and wet-dry tropics, understanding of stream processes, geomorphic thresholds and bank retreat rates is limited, apart from the obvious hydrological and climatological differences (Section 2.1 and 2.2). In particular, the rate of bank retreat of these systems has received inadequate attention given the highly variable climate and hydrology of the region and the considerable value of ecosystems, infrastructure and land adjacent to many of these systems.

This chapter addresses this issue by investigating the rates and mechanisms of retreat of the three study streams in response to the 2003/2004 wet season and comparing them with other tropical streams and the worldwide data presented in Section 1.5. In-stream erosion variation is also discussed with reference to the erosion variation model of Abernethy and Rutherfurd (1998). The objectives were to:

- survey the geomorphic characteristics of the banks;
- determine overall shifts of the bankfull position of the bank;
- measure variations in erosion at different positions up each study bank;
- identify the types of erosion that occur in each study stream;
- relate the rates and types of erosion to the different hydrological regimes and to the wet seasons experienced in all of the study streams;
- quantify the magnitude of the 2003/2004 wet season in all study streams;
- identify other factors that may have played a role in any erosion that occurred; and
- compare the study results with worldwide data.

3.2 Methods

The flowchart below (Figure 3.1) provides a brief summary of the above aims and the approach taken to satisfy each aim.

3.2.1 Cross-section establishment

For theoretical and practical reasons, the 'planimetric resurvey' and 'repeated cross-profiling' methods of measuring bank retreat and erosion of Lawler (1993a) were applied. A *Leica* EDM (total station) was used for surveying. These techniques were preferred over potentially more detailed methods, such as standard erosion pins or Photo-Electronic Erosion Pins (see Lawler and Leeks 1992) for several reasons:

- repeated channel survey along established cross-sections can record changes to the entire channel cross-sectional shape and are not limited to measuring bank position; this is especially useful if bed erosion and bar accretion are causing lateral retreat of the eroding bank;
- repeated cross-profiling provides a safer method for measuring bank erosion than erosion pins in that the surveying reference points (stakes) are less likely than pins to be completely removed by floods (Lawler 1993a, Prosser *et al.* 2000). Thus, they are more likely to provide a long-term erosion guide. This advantage was especially relevant in this study, as the streambanks were largely composed of highly erosive material;
- cross-profiling methods remove the possibility of artefact effects, as little interaction occurs with the bank face; and
- the use of a total station to survey banks removes the detail and accuracy problems associated with other surveying technology (e.g. dumpy level, inclinometer, datum technique). The Leica total station used had a reported accuracy of 2 mm.

1. Did the study streambanks retreat or accrete during the 2003/2004 wet season?

↓

Approach:
- Pre- & post- wet season cross-sections to establish retreat rates of the bank
- ANOVAs of retreat rates calculated for each site to identify differences between & within streams

2. What types of erosion mechanisms occurred & how much did they contribute to retreat?

↓

Approach:
- Erosion types classified in field
- Descriptive statistics used to show the contribution of each erosion type to retreat rates

3. Hydrological description of the 2003/2004 wet season

↓

Approach:
- Thornton Creek (TH) & Liverpool Creek (LI) gauge data used to measure flood height/stage & durations during the wet season
- Flood-frequency analysis of LI gauge data to provide an estimate of its relative size
- Jarra Creek (JA) flood information estimated using Manning's equation & interpretation from LI data.

4. How did the wet season affect different streams?

↓

Approach:
- *t*-test between retreat rates & flood stages in LI to identify any relationship
- Assumptions made in JA based on LI data & TH based on short gauge history

5. How does the data of the present study compare with previous data?

↓

Approach:
- Regressions between width/drainage area & retreat rate & width & retreat rate as a percentage of width to compare with established models.

Figure 3.1 – Summary flowchart illustrating the approach taken to address the chapter aims.

The initial condition of sites was described in September 2003, prior to the 2003/2004 wet season. At each study site, a cross-section was measured at right angles to the channel edge at the time of survey. Survey points along the cross-section were selected according to where changes in slope occurred. The total station was placed in a position where all points along the cross-section could be seen. Cross-section length varied according to channel width, but always extended past bankfull width. Bankfull width was measured as the distance between the top of the lowest bank to the opposite bank. The top of the lowest bank was clearly distinguishable in the three study streams as there was clear distinction between the channel and floodplain at all sites.

Survey stakes were driven into the ground to provide GPS-locatable benchmarks for future monitoring. At each site, one stake was placed at the total station survey point and up to five other stakes were placed on either side of the channel in relatively hidden locations to reduce the possibility of human interference or removal by floods. If present, permanent tie points (trees, telegraph poles, fence pole or building) were surveyed to further reduce the effect of any site tampering (Figure 3.2).

In the case of overhanging banks, the profiler methodology outlined by Hudson (1982) was used. Dumpy level stadia rods were used to measure overhanging sections and these measurements were later incorporated into the site profile (Figure 3.3).

In addition to measuring change in channel cross-sectional morphology, the boundaries between sedimentary units were also surveyed. The upper and lower limits of each stratum were recorded using the total station so that stratigraphy could be tied in to bank geometry. The bank top and current water level of both of the banks were also surveyed 100-200 m upstream and downstream of the cross-sections at 1.0-2.0 m intervals to obtain an overall planform for each site for analysis of curvature.

3.2.2 Erosion rates and types

Each study site was revisited after the 2003/2004 wet season (May-June). Using the survey stakes as reference points, the total station position and, subsequently, the cross-section location and angle were determined (Figure 3.2). Once again, the entire bankfull cross-section width was surveyed to provide pre- and post-flood channel positions and geometry. After field data collection was complete, pre- and post- wet season comparative channel profiles were drawn to measure shifts in bank position and shape. Erosion occurrence was measured at 0.5 m intervals up the bank from the bottom of the bank (bank toe) to its top. However, in this chapter, only five measurements of erosion up the bank are used – toe erosion, erosion 0.5 m above the toe, mid-bank erosion, erosion 0.5 m below the bank top and bank-top erosion. Bank-top erosion was used as an indication of fluctuations in overall bank position. The other positions were used to gauge differences in erosion rates at different depths up the bank.

Erosion occurrences were classified into types according to Abernethy (1999), Abernethy and Rutherfurd (1998), and Kapitzke *et al.* (1998) (Figure 3.4). Direct scour (type a) was divided into two types – toe scour and whole bank scour, according to whether only the toe or the entire bank were being scoured.

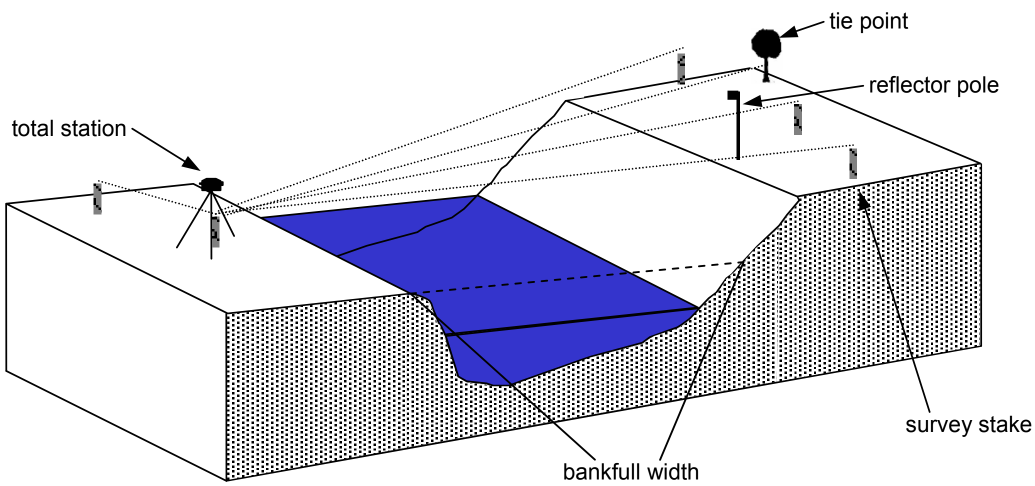


Figure 3.2 – Method of monitoring bank position, using semi-permanent reference points and permanent tie points on either side of the channel.

Cross-section position is determined from its relative position to and angle from reference points (modified from Lawler (1993a)).

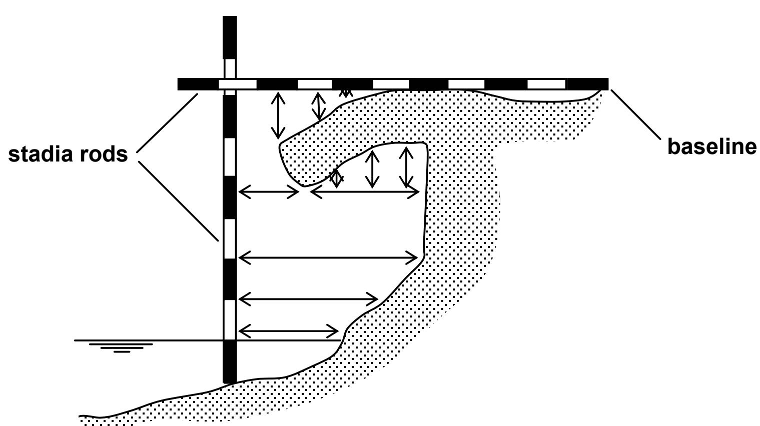


Figure 3.3 – Profiler methodology of Hudson (1982) and Lawler (1993a), where stadia rods are used to measure overhanging sections.

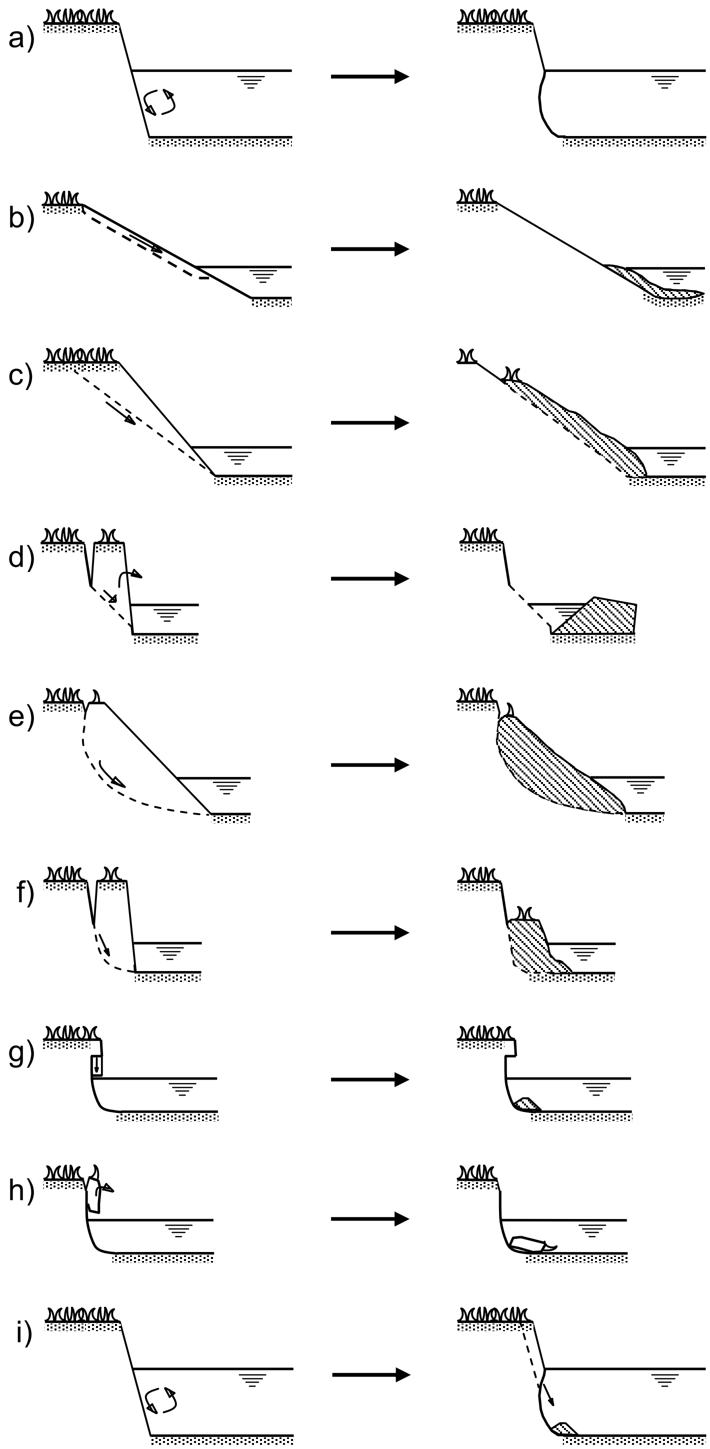


Figure 3.4 – Bank erosion mechanisms, including entrainment and failure modes: a) direct scour; b) shallow failure; c) planar failure; d) slab failure; e) rotational failure; f) translational failure; g) tensile cantilever failure; h) beam cantilever failure; and i) scour followed by immediate slippage of upper bank.

Note that these erosion/retreat mechanisms do not necessarily occur independently. Failures are commonly a composite of these schemes.

3.2.3 The 2003/2004 wet season

Flow discharges and specific stream powers over the wet season were measured and calculated to identify flows with high potential to affect channel form, following Baker and Costa (1987) and Urban and Rhoads (2003). This study was concerned with overall effects of the entire wet season, so analysis of total wet season discharge (rather than maximum instantaneous discharge) was performed.

In the Thornton and Liverpool Creek reaches, where stream gauges were present, site discharges and specific stream powers were interpolated from the stream gauge data. Gauge data was obtained from the Queensland Department of Natural Resources and Mines (NRM) (Liverpool Creek) and CSIRO Davies Laboratory (Thornton Creek). Data sets were small for both gauged streams (Liverpool Creek – 34 years; Thornton Creek – 3 years). Thus, wet season Average Recurrence Intervals (ARIs) were only calculated for Liverpool Creek through flood frequency analysis (FFA) of the gauge data. The FFA was based on the log-Gumbel distribution that combined accurately with the partial duration series (PDS) data. The analysis used a flood base level of 100 cumecs. Increasing or decreasing this base level made little difference to the overall analysis.

Gauge data from both streams enabled calculation of the recent wet season flow characteristics and generalised flow characteristics (average discharge, seasonality, flood stage, duration etc) for both streams. Jarra Creek reaches had no available stream gauge data; however, observations during flooding demonstrated that flow levels reached approximate bankfull stage, so bankfull discharges were estimated by calculating velocity using Manning's equation:

$$v = \left(R^{0.66} s^{0.5}\right) / n$$

where v = mean stream flow velocity (m s^{-1}), R = hydraulic radius, s = channel slope (m m^{-1}) and n = Manning's roughness coefficient. Velocity was then used to calculate discharge by multiplying it by channel capacity:

$$Q = v \times C$$

where Q = discharge (m^3 s^{-1}) and C = channel capacity (m^2). After calculating discharges for all sites, specific stream power was computed, using the equation:

$$\omega = \gamma Q s / w$$

where ω = stream power per unit boundary area (Watts/m^2), γ = specific weight of the fluid (9800N/m^3 for clear water) and w = water surface width (m).

3.2.4 Statistical analysis

ANOVAs and *post hoc* Tukey's tests were conducted on the overall bank retreat rates of each study stream and on erosion rates at the different intervals up the bank. ANOVAs on both absolute and width-standardised data were conducted. This enabled regime-based comparisons to be made between the study streams and the relationship between hydrological regime and bank erosion to be determined, while removing the effect of stream size. Separate ANOVAs were conducted excluding the effect of cantilever failures on retreat to remove the bias they caused in the huge retreat rates obtained in Jarra Creek.

3.2.5 Analysis of bank retreat rates according to flood stage

Erosion rate data (at 0.5 m below the bank top) for each Liverpool Creek site was separated into two groups according to whether the flow overtopped the bankfull stage at each site. This divided the data according to its flood stage relative to total channel capacity. A *t*-test was then performed on this data to determine whether any differences in erosion rate occurred between the groups and thus determine if there was a link between flood stage and retreat rate. Erosion rate at 0.5 m below the bank top was used, as opposed to bank top erosion data, to remove the effect of gradual channel-floodplain divisions.

3.2.6 Comparison of results with worldwide data

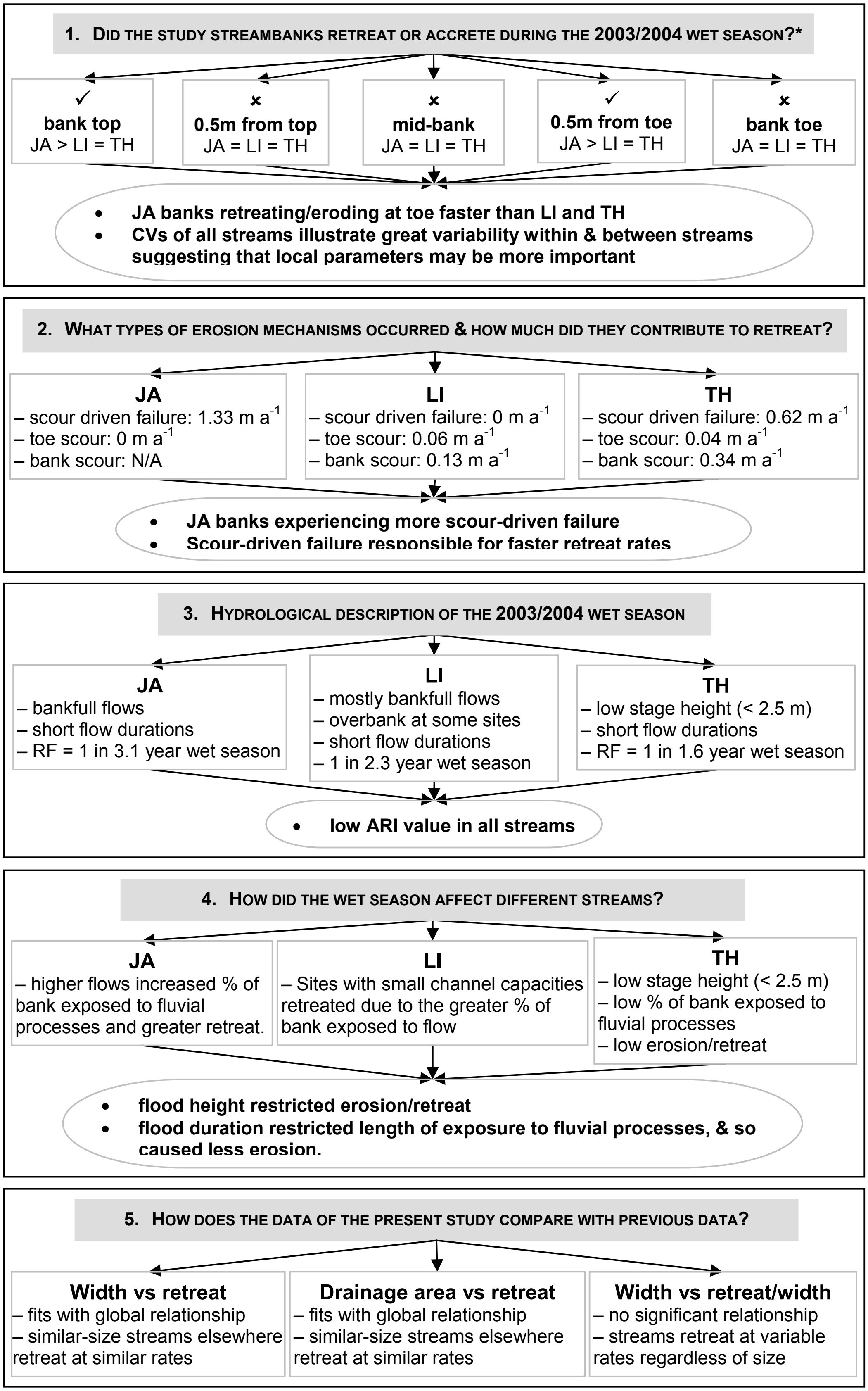
Regressions were conducted using worldwide bank retreat rates and stream width and drainage area respectively (Section 1.5). Another regression was performed between width and bank retreat rates as percentages of width to remove the influence of scale on retreat rates. The data obtained from the three study streams was incorporated into these comparisons to determine how they compared with worldwide data, in a similar way to Hooke (1980).

3.3 Results

Figure 3.5 provides a summary of the results measured and calculated for each of the chapter aims.

3.3.1 The 2003/2004 wet season

Based on total discharge, the 2003/2004 wet season of Liverpool Creek had an ARI of 2.27. It reached near-bankfull height at its gauge twice, once in February and once in March, for no longer than one day for each event (February ARI = 1.31, March ARI = 1.35). Figure 3.6 shows the 2003/2004 wet season ARIs relative to the gauge history of Liverpool Creek. With the exception of sites LI0004 and LI0010, bankfull stage height was also reached at all other sites during both gauge bankfull flows (Figure 3.6). Note that the 'bankfull' line in Figure 3.6 represents total channel capacity, as measured by the cross-sections (Section 3.2.1) and not actual bankfull position, which is also influenced by conditions and channel size upstream. The increase in discharge between the gauge and the most upstream site (LI0002) is largely due to tributary inflow and the distance between the gauge and site LI0002.



* ✓ indicates a significant result; × indicates a non-significant result

Figure 3.5 – Flowchart summarising the results relevant to each chapter aim.

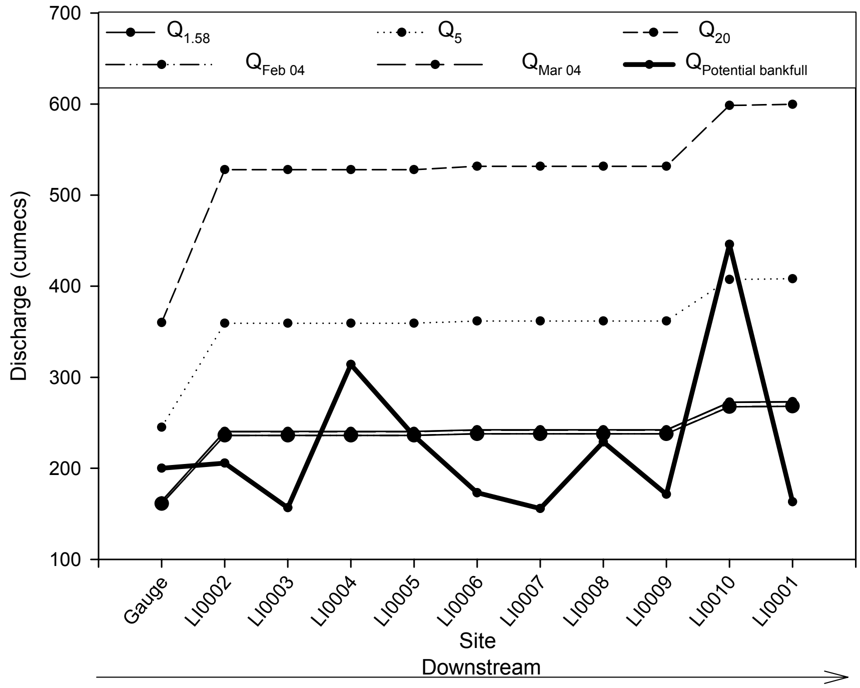


Figure 3.6 – Discharges of Liverpool Creek with various ARI values.
Note that the apparent double line near the bottom of the graph represents three similar flows ($Q_{1.58}$, $Q_{Feb\ 04}$ and $Q_{Mar\ 04}$). Note that the sites are not equally spaced downstream (see Figure 2.16).

Flows on Jarra Creek during the 2003/2004 wet season reached bankfull stage twice at all sites (as reported by the land owner). The presence of fresh debris in trees and vegetation at bankfull level at most sites confirms that Jarra Creek experienced approximate bankfull flows during the wet season (Figure 3.7). Rainfall data from the Tully Sugar Mill Composite gauging station also suggests that Jarra Creek experienced a 1-in-3.1 year rainfall event, with 3256 mm falling at this station (Clewett *et al.* 2003).

The gauge data record on Thornton Creek was too short to provide any useful information as to the ARI of the wet season flows. However, rainfall data from nearby Mirambeena gauging station shows that the 2003/2004 wet season had a recurrence interval of 1.6 years, with 339 mm falling at the station (data source: Bureau of Meteorology, 2005). Furthermore, stream gauge data showed that the 2003/2004 wet season produced several flow events below bankfull level, with rapidly rising and falling hydrographs. These flows reached a maximum height of 2.13 m above bed level and discharge of 79.11 cumecs at the gauge for a maximum of 12 hours. Figure 3.8 shows the 2003/2004 wet season flows in relation to the maximum bankfull flows of the Thornton Creek sites. It is evident that flows were much lower than bankfull at all sites. As with Figure 3.6, the 'bankfull' line in Figure 3.8 represents total channel capacity at each site, as measured by the cross-sections (Section 3.2.1).

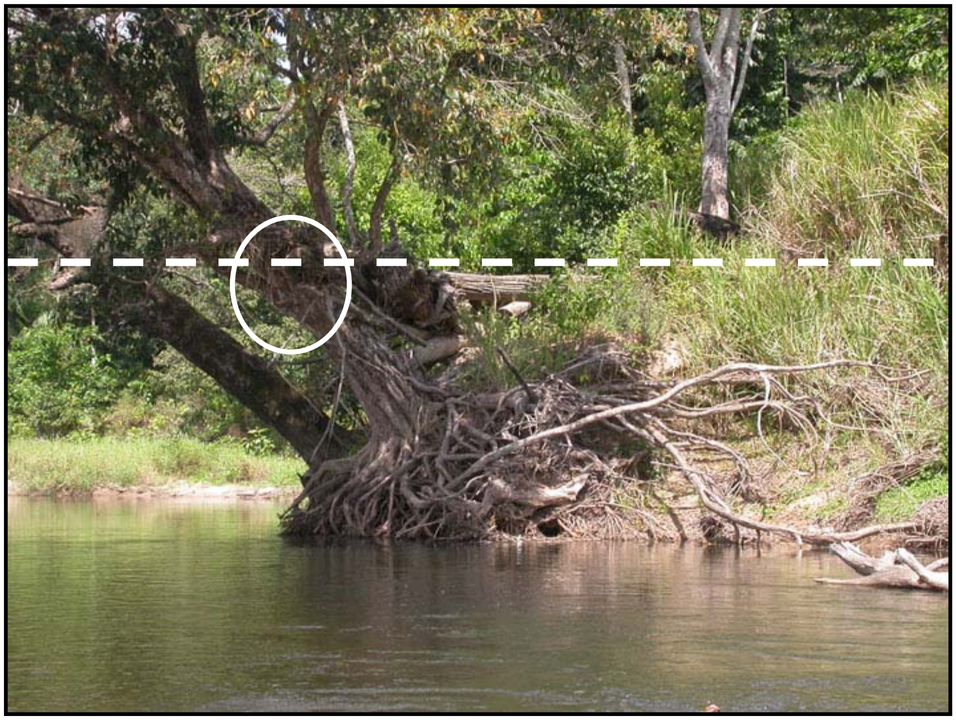


Figure 3.7 – Debris left by the 2003/2004 flows on Jarra Creek.
The white circle highlights the debris and the dashed white line shows the approximate bankfull level.

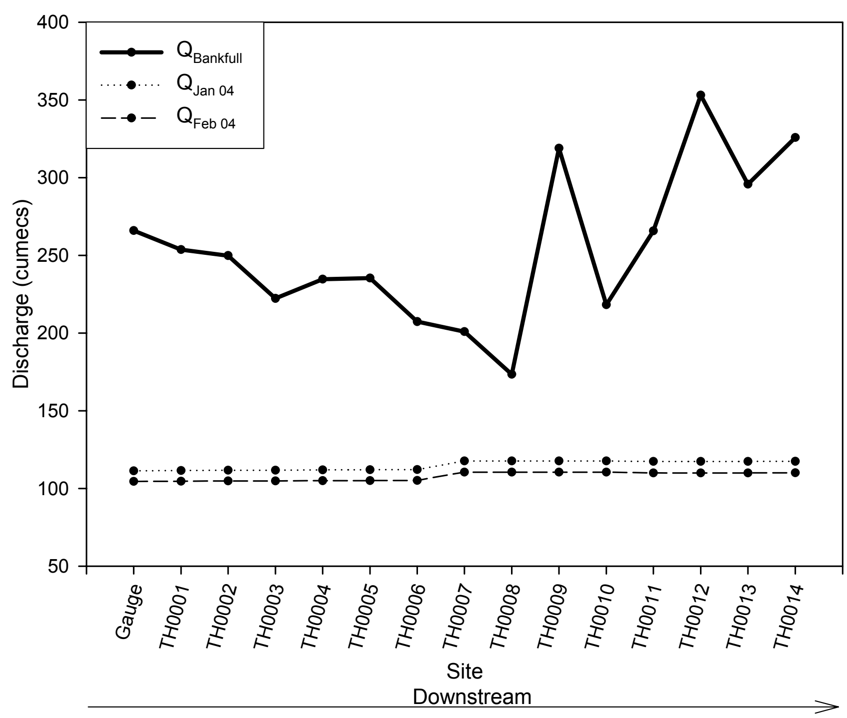


Figure 3.8 – Discharges of the 2003/2004 wet season on Thornton Creek, relative to bankfull flow.
Sites are ordered left to right in a downstream direction.

3.3.2 Erosion rates

Appendix A shows cross-sections from each site and illustrates the retreat that occurred during the wet season. Appendix B contains photographs of each site illustrating their relative stability and the local prevailing conditions. Great variability existed in bank erosion and retreat rates between and within streams. This is indicated by the high coefficients of variation and indicates that local controls dominated erosion rates (Table 3.1).

<u>Jarra Creek</u>

Overall shifts in bank position (bank-top erosion) averaged 0.94 m a^{-1} (± SE 0.42 m a^{-1}), and ranged from -0.6 m a^{-1} to 2.99 m a^{-1} (Table 3.1). Only four sites, however, eroded more than 0.5 m a^{-1} (JA0003, JA0004, JA0006, JA0010), while two sites were static (JA0002, JA0007) and two sites aggraded slightly (JA0008, JA0009). Average erosion near the bank toe (+ 0.5 m) showed similarly high but variable erosion, averaging 1.35 m a^{-1} (± SE 0.42 m a^{-1}) and ranging from 0 m a^{-1} to 4.31 m a^{-1}. Mid-bank erosion rates were low, but observations of banks *in situ* showed that failed material accumulated at mid-bank, reducing erosion at these points. This failed material often became part of the bank and provided extra cohesion and protection against fluvial processes, so it was surveyed as such. Similarly low readings at the bank toe resulted from similar failed deposits, but were also a result of sporadic bed deepening. Erosion of the bed coupled with lateral erosion results in the bank-toe remaining in a similar position laterally. Figure 3.9 shows examples of erosion occurring on Jarra Creek.

<u>Liverpool Creek</u>

The Liverpool Creek study sites underwent an average overall bank retreat rate of 0.06 m a^{-1} (±SE 0.05 m a^{-1}). Most sites remained stable, with rates varying between 0 m a^{-1} and 0.38 m a^{-1}, while only two sites moved more than 0.3 m a^{-1} (LI0003, LI0006). Although rates near the bank toe (0.5 m above the toe) ($\bar{x}$ = 0.32 m a^{-1} ± 0.17) and at the toe ($\bar{x}$ = 0.33 m a^{-1} ± 0.25) were faster than overall bank retreat (suggesting undercutting) they were considerably lower than rates observed on Jarra Creek. Average erosion rates at other bank heights were of similar magnitude to overall bank retreat rates. Table 3.1 shows all erosion rates recorded on Liverpool Creek. Figure 3.10 shows examples of erosion occurring on Liverpool Creek.

<u>Thornton Creek</u>

Average bank retreat of Thornton Creek study sites was minimal ($\bar{x}$ = 0.17 m a^{-1} ± 0.08). Similar average erosion rates occurred mid-way up the study banks ($\bar{x}$ = 0.23 m a^{-1} ± 0.11) and near the top of the banks (0.5 m below bank top) ($\bar{x}$ = 0.22 m a^{-1} ± 0.11). However, rates near the toe (0.5 m above bank top) were markedly higher and more variable than at other locations up the banks ($\bar{x}$ = 0.41 m a^{-1} ± 0.19). Table 3.1 lists the rates of erosion recorded at all sites on Thornton Creek. Examples of erosion that occurred on Thornton Creek are shown in Figure 3.11.

Table 3.1 – Erosion rates of banks at each study site

Site*	Width (m)	Erosion Rate (m a^{-1})†				
		Bank top (bank retreat)	0.5 m below top	Mid-bank	0.5 m above toe	Bank toe
JA0001	101.18	0.42	0.42	0.18	0.90	0.30
JA0002	79.06	0.00	0.11	0.24	1.26	0.54
JA0003	97.88	2.99	3.11	3.23	2.87	1.63
JA0004	55.53	2.50	1.75	0.31	1.20	-0.66
JA0005	37.65	0.36	-0.18	-0.13	-0.21	-0.24
JA0006	62.12	2.71	2.69	3.22	4.31	0.00
JA0007	55.77	0.00	-0.30	-0.21	0.38	0.36
JA0008	48.00	-0.24	-0.48	-1.44	0.32	1.11
JA0009	67.77	-0.60	-0.36	-0.18	1.08	0.00
JA0010	83.77	1.31	1.43	1.26	1.44	0.00
Mean	**68.87**	**0.94**	**0.82**	**0.65**	**1.35**	**0.30**
SE	**21.78**	**0.42**	**0.42**	**0.48**	**0.42**	**0.21**
CV	**31%**	**141%**	**163%**	**233%**	**98%**	**218%**
LI0001	39.57	0.00	0.48	0.05	-0.60	0.00
LI0002	49.79	-0.12	0.12	0.05	0.24	0.00
LI0003	54.46	0.38	0.42	0.21	0.30	0.00
LI0004	45.53	0.00	0.00	0.00	0.00	0.36
LI0005	34.04	0.00	0.00	0.03	0.12	0.30
LI0006	37.44	0.36	0.21	0.00	0.90	0.90
LI0007	50.64	0.00	0.46	0.09	1.17	0.00
LI0008	94.04	0.00	0.00	0.00	0.14	-0.65
LI0009	89.36	0.00	0.00	0.20	-0.04	0.03
LI0010	80.42	0.00	0.21	0.12	0.96	2.33
Mean	**57.53**	**0.06**	**0.19**	**0.08**	**0.32**	**0.33**
SE	**18.19**	**0.05**	**0.06**	**0.03**	**0.17**	**0.25**
CV	**39%**	**268%**	**105%**	**106%**	**169%**	**246%**
TH0001	50.05	0.18	0.24	0.20	1.92	2.75
TH0002	63.25	0.00	0.00	0.18	0.84	0.60
TH0003	53.90	0.42	0.15	0.00	0.12	0.00
TH0004	58.85	0.30	0.18	0.12	0.66	0.33
TH0005	54.45	0.00	1.20	0.21	0.60	0.78
TH0006	63.80	0.30	0.30	1.26	0.24	0.30
TH0007	63.17	0.30	0.18	0.24	0.90	0.00
TH0008	64.99	0.00	0.00	0.11	0.24	0.24
TH0009	56.99	0.93	0.70	0.48	0.74	0.00
TH0010	56.78	0.00	0.00	0.18	-0.18	-0.12
TH0011	45.65	0.00	0.00	-0.16	-0.18	0.00
TH0012	56.10	0.00	0.00	0.00	0.06	0.00
TH0013	51.15	0.00	0.00	0.45	0.42	0.12
TH0014	74.80	0.00	0.12	0.00	-0.60	0.00
Mean	**58.14**	**0.17**	**0.22**	**0.23**	**0.41**	**0.36**
SE	**15.54**	**0.08**	**0.11**	**0.11**	**0.19**	**0.23**
CV	**13%**	**154%**	**155%**	**146%**	**149%**	**206%**

* Site codes: JA = Jarra Creek; LI = Liverpool Creek; TH = Thornton Creek
† A negative symbol indicates the occurrence of aggradation

A

B

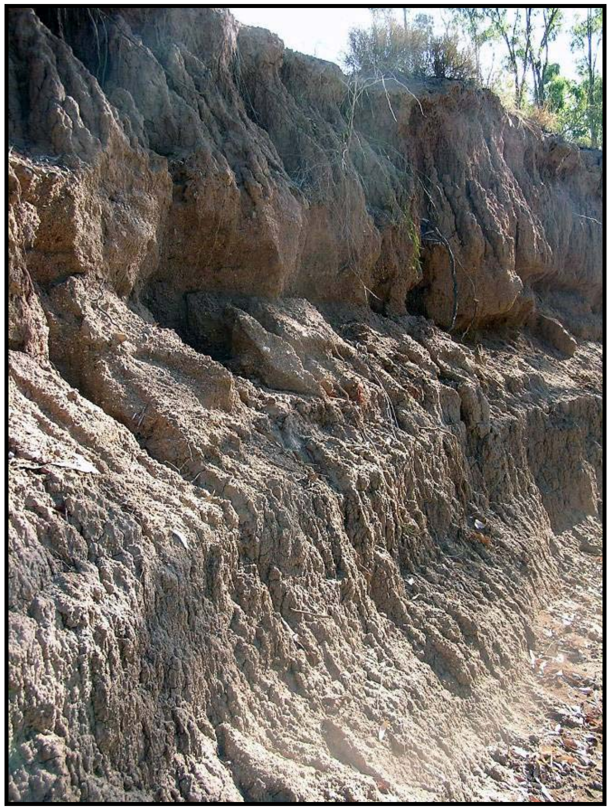
Figure 3.9 – Examples of erosion occurring on Jarra Creek: (A) scour followed by immediate slippage occurring at JA0003; (B) scour followed by failure just upstream of JA0010.

Note the failed portions at the bank toe protecting the bank from further scour.

A

B

Figure 3.10 – Examples of erosion occurring on Liverpool Creek: (A) toe scour at LI0006, showing the armouring effect provided by roots; (B) scour followed by cantilever failure at LI0010; remnant failed portions protect the toe against further scour.



A

B

Figure 3.11 – Examples of erosion occurring on Thornton Creek: (A) scour occurring at TH0002, showing different rates of scour occurring in different sedimentary units; (B) cantilever failure upstream of TH0014.

3.3.3 Erosion mechanisms

While most erosion mechanisms outlined in Figure 3.4 were observed at several locations in each study stream, only three major erosion mechanisms occurred in the study reaches. Scour (Figure 3.4a) (including whole bank scour and bank toe scour) was the most common type of erosion, with some banks also subject to cantilever failures following toe scour (Figure 3.4g, h) or immediate slippage of the upper bank after scour (Figure 3.4i). These two erosion mechanisms will be considered together as a single mechanism (scour followed by failure) for this chapter as they are closely interrelated.

The absence of all other types of failure can be attributed to the presence of non-cohesive strata in most sites that are conducive to scour-related failures. Figure 3.10a shows an example of toe scour occurring on Liverpool Creek, while Figure 3.9b shows cantilever failure occurring on Jarra Creek following toe scour. Table 3.2 lists the mean site bank retreat rates and toe erosion rates resulting from each erosion mechanism. Values were calculated by obtaining the sum of the maximum amount of retreat/erosion occurring at each site as a result of each erosion mechanism then dividing it by the number of sites that were subject to that type of erosion.

Only failure/slippage after toe scour resulted in substantial (> 0.5 m a^{-1}) erosion rates.

Table 3.2 – Mean erosion rates occurring via different erosion mechanisms in Jarra, Liverpool and Thornton Creeks in the 2003/2004 wet season.

Erosion mechanism	Mean maximum erosion rate (m a^{-1})*					
	Jarra Creek		Liverpool Creek		Thornton Creek	
	Toe	Bank-top retreat	Toe	Bank-top retreat	Toe	Bank-top retreat
Toe scour	0.38	0.00	0.82	0.06	0.80	0.04
Bank scour	-	-	0.19	0.13	0.34	0.34
Bed-bank interface scour	-0.21	0.36	-	-	-	-
Scour with failure	1.86	1.33	-	-	0.82	0.62

* - indicates that no erosion of this type occurred

Jarra Creek

Failure or slippage associated with toe scour was responsible for the most erosion and overall bank retreat during the study period. It occurred at seven sites and accounted for an average near-toe erosion rate of 1.86 m a^{-1} at each site, with near-toe erosion rate exceeding 4.30 m a^{-1} at one site (JA0006). This type of erosion also accounted for an average bank-top retreat rate of

1.33 m a^{-1} (Table 3.2). Toe scour only occurred by itself at one site (JA0007). It accounted for an erosion rate of 0.38 m a^{-1} at the toe, but was not responsible for any erosion at the bank top, resulting in static channel and bank conditions at both scouring sites. Bed scour accounted for little lateral shift in bank position at most sites, but at one site (JA0005) it was responsible for 1.21 m of bed incision.

Liverpool Creek

On average, less than 0.15 m a^{-1} of overall bank retreat occurred as a result of any erosion mechanism during the study period. No sites experienced upper bank failure (Table 3.2). Toe scour was the major type of erosion that occurred on Liverpool Creek, occurring at four sites (LI0002, LI0006, LI0007, LI0010). It accounted for a site average of 0.82 m a^{-1} of erosion at the toe, but was responsible for very little overall bank retreat (site $\overline{x}$ = 0.06 m a^{-1}). Full bank scour accounted for an average of 0.19 m a^{-1} at the toe, while resulting in an average of 0.13 m a^{-1} of overall bank retreat. Bed incision occurred at several sites, accounting for 0.56 m of lowering at LI0010, 0.38 m at LI0007 and negligible incision at LI0004, LI0005, LI0006, LI0008 and LI0009.

Thornton Creek

Toe scour dominated erosion at the Thornton Creek study sites. It accounted for a site average of 0.80 m a^{-1} of erosion at the toe and 0.04 m a^{-1} of overall bank retreat. Full bank scour accounted for an average of 0.34 m a^{-1} of toe erosion, while upper bank failure was responsible for a site average of 0.82 m a^{-1} of toe erosion and 0.62 m a^{-1} of overall bank retreat. Little bed scour occurred, resulting in no lateral changes in bank position or incision.

3.3.4 Stream and climatological region variation

ANOVAs on absolute and width-standardised data returned similar results because as the three study reaches were of similar size, width standardisation had little effect on the data. Therefore, only the ANOVAs performed on absolute data are reported here. The ANOVA of the mean bank-top erosion rates showed that rates were significantly higher in Jarra Creek than either Liverpool Creek or Thornton Creek (Figure 3.12). However, no significant difference existed between bank-top erosion rates of Liverpool Creek and Thornton Creek, with both experiencing low average bank retreat rates (0.06 m a^{-1} & 0.17 m a^{-1} respectively). Significant differences were also observed in retreat rates between Jarra Creek and both Liverpool Creek and Thornton Creek within 0.5 m of the bank toe (ANOVA: $F_{2,\ 31} = 4.55$, $p = 0.02$; Tukey's: JA -LI & TH < 0.04). However, there was no significant difference in bank retreat rate between Liverpool Creek and Thornton Creek (Tukey's: LI-TH > 0.9). Average erosion rates at all other intervals up the study banks on all study streams were not significantly different.

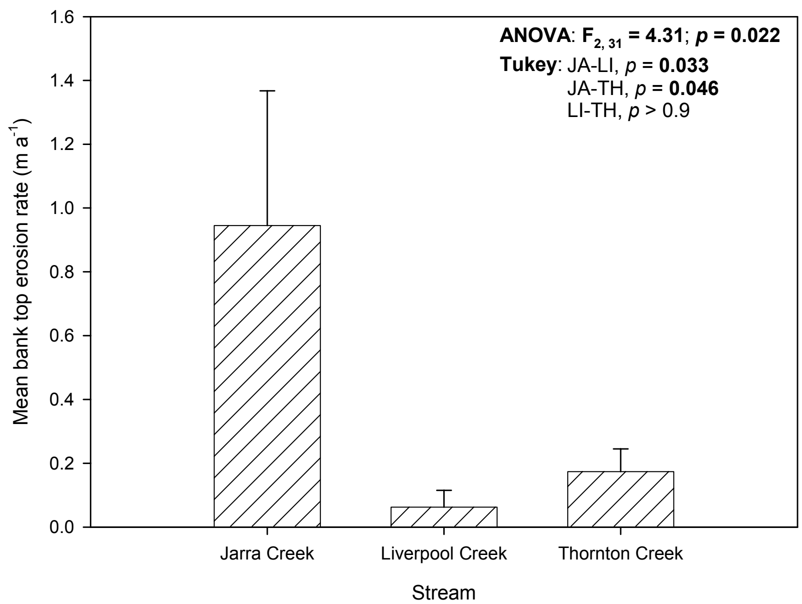


Figure 3.12 – Mean bank-top erosion rates of each study stream.
Error bars show standard error. The results of an ANOVA between streams are indicated.

Given that observations of the occurrence of erosion mechanisms in the study streams indicated that toe scour followed by failure dominated only in Jarra Creek, a second ANOVA was performed excluding this erosion mechanism from the analysis to isolate the effect of scour on erosion rates. The second ANOVA produced contrasting results from the initial one (Table 3.3). Only erosion mid-bank was significantly greater in Jarra Creek than either Liverpool Creek or Thornton Creek. Average erosion at all other intervals up the bank, including the bank top, were not significantly different between study streams. Hence, without the inclusion of the banks undergoing failure, rates of bank retreat of the Jarra Creek study sites were similar to those on both Liverpool Creek and Thornton Creek.

3.3.5 Flood stage and retreat rate

In Liverpool Creek, a significant relationship existed between flood stage and erosion rate just below the bank top ($t = 2.36$, $p = 0.046$). Most sites that overfilled their channel capacity experienced retreat to some degree. This indicated that those sites with larger channel capacity and so a greater percentage of their bank not exposed to fluvial processes, retreated significantly less. For instance, LI0001, LI0003, LI0006 and LI0007 all theoretically overbanked and subsequently eroded more than 0.2 m a^{-1} (Figure 3.6 and Table 3.1).

Table 3.3 – Results of an ANOVA performed on erosion at different locations up the banks of each study stream.

Location on bank		Sum of Squares	df	Mean square	F	*p*
Bank top	Between groups	0.017	2	0.01	0.28	0.76
	Within groups	0.702	23	0.03		
	Total	0.719	25			
Top – 0.5 m	Between groups	0.54	2	0.27	3.44	0.06
	Within groups	1.79	23	0.08		
	Total	2.33	25			
Middle	Between groups	1.07	2	0.54	3.99	0.03
	Within groups	3.09	23	0.13		
	Total	4.16	25			
Toe + 0.5 m	Between groups	0.04	2	0.02	0.06	0.95
	Within groups	8.20	23	0.36		
	Total	8.24	25			
Bank toe	Between groups	0.059	2	0.03	0.05	0.95
	Within groups	13.49	23	0.59		
	Total	13.55	25			

3.3.6 Comparisons of bank retreat rates with existing data

Comparisons between reported rates of bank retreat provide a useful approximation of how rates vary according to certain characteristics, regardless of the complications introduced by local factors (Section 1.5). Hooke (1980) provided comparisons between worldwide studies, using drainage area as the independent variable. The relationship followed a logarithmically increasing trend, similar to that in Section 1.5.7. It is evident that the banks of the study streams moved at similar rates to comparable streams worldwide (Figure 3.13). A similar comparison replacing drainage area with width produced similar results. The retreat rates measured in this study were again well within the recorded range (Figure 3.14).

The inclusion of the data from the present study into the regression between bank retreat rates and retreat rates as percentages of width again showed no distinct relationship (Figure 3.15). It also showed that retreat rates in the present study were within the worldwide range. All study sites that moved had widths between 50 and 100 m. The worldwide mean bank retreat rate for streams of this size is 5.04% of stream width. The faster-eroding sites on Jarra Creek moved at average rates for streams of similar size; however, all other sites moved at rates below the worldwide average.

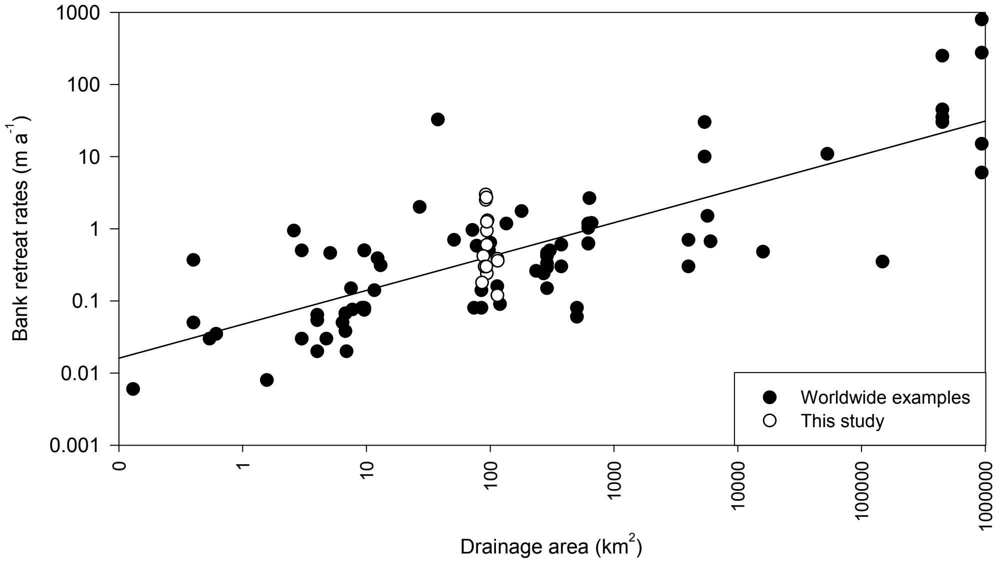


Figure 3.13 – Relationship between bank retreat rate and drainage area.
The linear regression line is fitted (log y = log(0.47x) - 1.32; r^2 = 0.60; p < 0.05). Worldwide data sourced from Hooke (1980), Hudson and Kesel (2000) and Lawler (1993a).

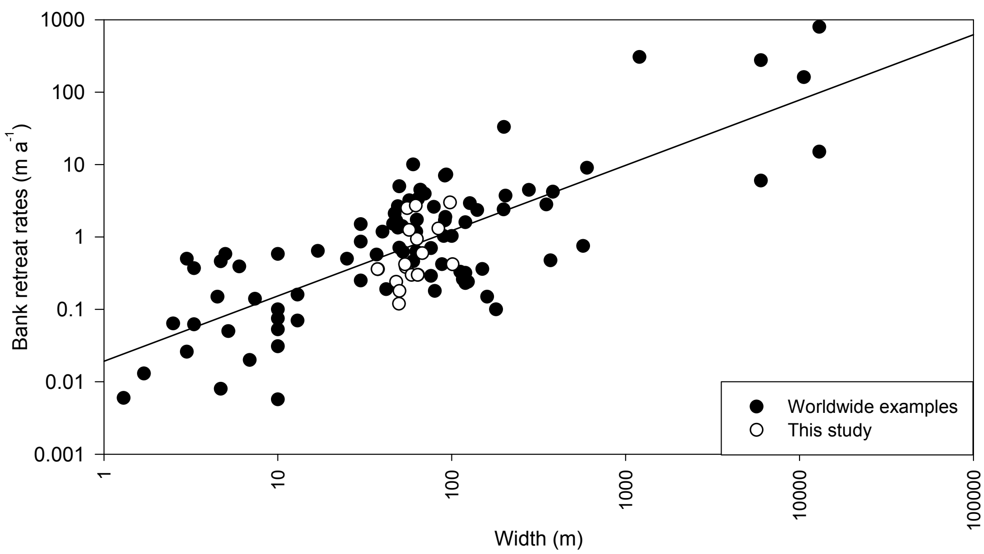


Figure 3.14 – Relationship between stream width and bank retreat rates.
The linear regression line is fitted (log y = log(0.9x) - 1.72; r^2 = 0.59; p < 0.05). Worldwide data sourced from Hooke (1980), Hudson and Kesel (2000) and Lawler (1993a).

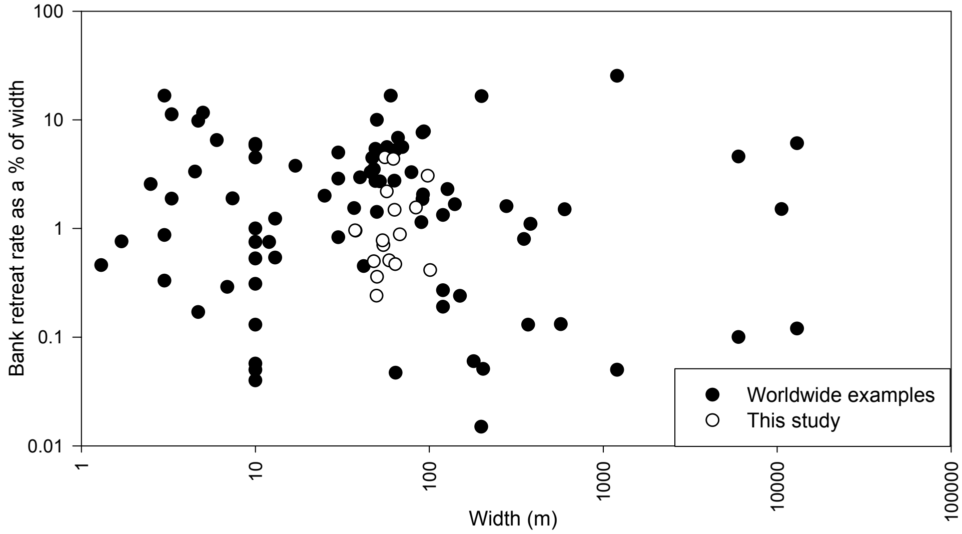


Figure 3.15 – Relationship between stream width and bank retreat rate as a percentage of stream width. No significant relationship was identified (r^2 = 0.02; *p* > 0.05).
Worldwide data sourced from Hooke (1980), Hudson and Kesel (2000) and Lawler (1993a).

3.4 Discussion

Mechanisms and rates of bank retreat and erosion were highly variable within the three study streams and were heavily influenced by local site parameters. These relationships are discussed further in Chapters 4 and 5. The discussion of this chapter focuses on (1) the marked variability in retreat and erosion rates within and between streams; (2) the link between flood stage and retreat rate in Liverpool Creek; and (3) comparisons with previous data.

3.4.1 Impact of the wet season

Jarra Creek was the only stream to experience > 1.0 m bank retreat (bank top erosion) during the 2003/2004 wet season. The lack of response of Thornton Creek was not unexpected – the low flood stage (2.13 m above bed at gauge) meant only small portions of its banks were submerged and subjected to fluvial processes. However, flow in Liverpool Creek exceeded bankfull flow in most locations, so more severe erosion could have been expected. Bankfull flows are important in controlling channel dimensions, form and shape, as the magnitude and frequency of these flows are at their optimum for controlling channel size and form (Gupta 1995, Wolman and Miller 1960). Significantly, the link between bank retreat rate and flood stage of Liverpool Creek identified in Section 3.3.5 suggests that those sites where the 2003/2004 wet season flows did not reach bankfull height retreated at slower rates. Thus, the flows may not have reached a high enough stage at these sites to perform geomorphic work on their banks.

The ARI of the wet season supports this and suggests that the stream is in fact adapted to regular flooding. The lack of response of Liverpool Creek banks to the 2003/2004 wet season may reflect the regular flooding history of Liverpool Creek. Flood regularity has been shown to be instrumental in dictating a channel's response to floods. Streams that experience bankfull flows regularly are less likely to change their form and shape in response to the flows (Baker 1977, Erskine 1996, Stevens *et al.* 1975). Regularly flooding tropical streams differ further from this norm as bankfull flows are even less effective at 'shaping' the channel than has been reported previously in temperate streams. Hence, rather than bankfull flows dominating channel formation, a series of less frequent flows provide most impact in determining channel change and stability (Gupta 1993, Gupta 1995 and Pickup and Rieger 1979).

The duration of peak discharge may have affected the low retreat rates in all three streams. The largest flood is not necessarily correlated with the greatest bank retreat. Rather, higher mobility is often more closely linked with the duration of wet periods associated with flooding (Couper and Maddock 2001, Simon *et al.* 1999, Wolman 1959). Both Liverpool Creek and Jarra Creek overbanked twice at most sites for a maximum of one day during the wet season, while Thornton Creek peaked twice at about 2.1 m for a maximum of 12 hours during the same period. Thus, only short interaction between the bank and peak flow occurred. Similarly, there was insufficient time for complete bank wetting from within the channel and the associated effects of rapid drawdown.

In all study reaches, in all three study streams, only one failure mechanism (scour-driven) occurred, and other mechanisms, driven by *in situ* bank characteristics, were absent. The short duration of the flooding in this study provides a plausible explanation for the lack of long-lasting effects although it may not be the sole reason. It may also explain the absence of failure mechanisms in reaches supposedly dominated by these mechanisms (Abernethy and Rutherfurd 1998). Casagli *et al.* (1997), Dapporto *et al.* (2003) and Simon *et al.* (2000) discuss the effects of pore-water pressure and related groundwater levels, bank saturation and matric suction on bank strength. These factors are related to bank wetting through changes in groundwater elevation, infiltration of precipitation or lateral infiltration of streamflow into the bank, all of which are directly related to flood duration (Dapporto *et al.* 2003, Simon *et al.* 2000). While severe scour can obviously be influenced by the entrainment time available in a particular flow event, its mechanisms operate on much shorter time-scales than bank-wetting processes. Thus, the dominance of scour and scour-led failure mechanisms on all study streams would appear to be due largely to the short nature of the high flows during the wet season. Wetter wet seasons might be expected to cause a wider range of failure mechanisms.

3.4.2 Stream and regional variation

There was considerable variation in erosion and retreat rate among sites in all study streams. The coefficient of variation of rates exceeded 90% for every interval up the bank on all streams (Table 3.1). The variability was greatest on Jarra Creek, where retreat rates ranged from 0 m a^{-1} to ~3 m a^{-1} with aggradation in some cases (indicated by the negative values in Table 3.1). Similar variation has been observed on the River Exe, UK (from 0.63 to 2.58 m a^{-1} – Hooke 1980), on the Luangwa River, Zambia (from 0 m a^{-1} to < 33 m a^{-1} – Gilvear *et al.* 2000) and, on a more local scale, between adjacent meander bends of the Mississippi River (Hudson and Kesel 2000).

Variations in bank retreat rate over the wet season are, therefore, not unusual, and the results of this study indicate neither long-term stability nor instability. Rather, they provide a snapshot that indicates that during the wet season some banks moved further than others. Variation in retreat (or its absence) does not necessarily imply long-term bank stability. Meander-bend development and erosion are intermittent by nature so a single bend can undergo highly variable rates of retreat from year to year, depending on the local bank characteristics (Brice 1973, Hickin 1974, Nanson and Hickin 1983, Nanson and Hickin 1986). One bend might erode 5 m in one year but be stable the next, while an adjacent bend might be stable the first year and erode 5 m the next. Clearly, a study based on one wet season cannot capture the full range of floods and their effects, but does provide evidence of bank behaviour under a particular suite of conditions.

Abernethy (1999) and Abernethy and Rutherfurd (1998) observed downstream changes in dominant erosion mechanisms along the Latrobe River, Victoria. They observed shifts from subaerial processes to direct fluvial scour to mass failure mechanisms according to distance downstream. All reaches in this study were located in the downstream floodplain reaches identified by Abernethy (1999) and Abernethy and Rutherfurd (1998) as being 'dominated' by mass failure mechanisms (see Figure 2.7). However, these mechanisms were far less prevalent than direct scour, except for several Jarra Creek banks undergoing toe scour-led cantilever failure/slippage. On the Liverpool Creek study reach, direct scour was the only active erosion mechanism.

Average rates of bank retreat were much higher in Jarra Creek than Liverpool or Thornton Creeks. Jarra Creek and Liverpool Creek were subject to similar hydrological and climatological influences, with high rainfall and associated bankfull flows at most sites, while Thornton Creek received less rain and was only filled to a maximum of about 50% capacity. Therefore, it was expected that banks of Thornton Creek would retreat much more slowly than those on Liverpool Creek or Jarra Creek. However, Jarra Creek banks retreated, on average, at a significantly higher rate than Liverpool or Thornton Creek banks, which retreated at similarly low rates, but this difference was due to a few highly erosive sites on Jarra Creek. Otherwise, the rates of retreat were similar across all three streams. These results indicate that with the exception of the highly erosive banks in Jarra Creek undergoing severe undercutting and associated failure, retreat of all banks was affected very little by the wet season, and that all streams moved at similarly low rates regardless of climate or flow regime.

Section 1.5 showed that a relationship exists between climate and bank retreat rates, with streams in tropical regions moving faster than those in temperate or cold temperate regions. Section 1.5 also showed that local factors can combine to provide variation in rates of bank retreat within climatological zones. The present study focussed on smaller-scale climatological variations by comparing streams in wet and wet-dry tropical regions. However, it found no significant role of these climatic differences on bank retreat, with both Liverpool Creek and Thornton Creek undergoing similarly low rates of retreat. However, the 2003/2004 wet season may not have been sufficiently large to have any major effect. Flows of greater recurrence interval and higher magnitude may produce different results. The differences in rates of retreat between the two wet tropical systems coupled with the similar rates of retreat of Liverpool Creek (wet tropics) and Thornton Creek (wet-dry tropics) is indication of the minimal climatic control over retreat variations between the three study streams. It also indicates that more local factors control these retreat rates. The following two chapters consider some of these factors, especially focusing on bank sediment and vegetation.

3.4.3 Comparisons with worldwide data

Although Jarra Creek moved at greater rates than Liverpool or Thornton Creeks, all streams fitted into global bank-retreat-drainage-area and bank-retreat-width relationships. That is, they moved at similar rates to other streams of comparable size, despite the fact that as tropical systems they are subjected to more frequent, higher-magnitude events and the higher stresses associated with these events than many others systems (Haines *et al.* 1988). While many of the worldwide studies report the effects of low recurrence flows, this study observed the effects of a relatively low magnitude, high frequency flow. Thus, the rates reported here may not be representative of the effects of less frequent large floods on the same streams. That is, a larger wet season may enhance the rates of bank retreat reported here. This is a common problem in comparing short-term studies that do not encompass all types of events in a particular system. For example, Erskine (1996) discusses bank retreat rates in the order of 0.1 m a^{-1} at a site on Wollombi Brook, south-eastern Australia, during a flood with a return period of 87 years. In comparison, some of the larger sites on the three study streams were of similar size, yet retreated at much greater rates irrespective of the fact that the 2003/2004 wet season had a return rate of 1-3 years. With no history of a channel's previous responses to floods, it is difficult to establish the effectiveness and relative significance of one particular flood event. Comparisons with worldwide studies are thus complicated by the fact that the relative effectiveness of the particular event is not known.

3.5 Summary

Most study sites underwent little erosion or bank retreat. However, where retreat occurred, it was dominated by direct scour processes. Cantilever failure or immediate upper bank slippage associated with direct scour was also observed on Jarra Creek. The dominance of scour produced relatively high average rates of erosion at the bank toe. However, most sites underwent little overall retreat over the study period.

In effect, regardless of the high quantity of erosion that occurred at some sites on Jarra Creek, no abnormally high rates were observed. Rates on Liverpool Creek and Thornton Creek were appreciably lower than expected, but were similar to bank retreat rates reported for other streams of comparable size. Climate appeared to play very little role in any inter-stream differences; however, the climate and hydrology, and the streams' adaptations to them meant that the wet season was not of high enough magnitude to produce significant rates of retreat. The general lack of response of the channels to the 2003/2004 wet season flows suggests that there is not a simple relationship between discharge and bank erosion or retreat and implies that several other factors may have implications for bank retreat. Several of these factors are discussed in the next chapter.

CHAPTER 4
BANK RETREAT AND ITS DRIVING FORCES

4.1 Introduction

The effects of climate and resulting hydrology of the 2003/2004 wet season on streambank stability on Jarra, Liverpool and Thornton Creeks were shown in the previous chapter to be small compared with the effects of more local factors. The literature suggests that bank stability is often controlled by a variety of local factors, such as discharge, stream power, curvature, bank geometry, sedimentology and stratigraphy and channel dimensions (e.g. Mosley 1975, Pizzuto and Meckelnburg 1989) (Section 1.5), and that to understand spatial variations in streambank stability, the influence of all of these factors must be considered.

Sediment type has a major influence on retreat rate in heterogeneous floodplains (Section 1.5). Sediment size, clay/gravel percentage constituents and stratigraphy influence bank cohesion and, therefore, bank stability (Dapporto *et al.* 2003, Ebisemiju 1994, Huang and Nanson 1998, Thorne and Tovey 1981). Vegetation density, root density and root strength have also been shown to affect bank retreat (Section 1.5). At a broad scale, confinement of bank retreat and channel metamorphosis has been attributed to the presence and removal of vegetation. (Allmendinger *et al.* 2005, Brooks and Brierley 2002, Geyer *et al.* 2000, Micheli *et al.* 2004). At a local scale, sediment cohesion, reduced adjacent stream flow, improved bank drainage and improved bank resistance and stability have all generally been attributed to root presence (Abernethy and Rutherfurd 1999a, 2000a, Hickin and Nanson 1984, Huang and Nanson 1997, Simon and Collison 2002, Thorne 1990).

In this study, the heterogeneous stratigraphy, vegetation and root density characteristics of the study sites provided the opportunity to examine relationships between these variables and bank retreat rates and types. This chapter focuses on this interconnectedness of bank retreat and stability with the different hydrological, vegetative, geomorphological and sedimentological characteristics of each study site during the 2003/2004 wet season. In particular, it:

- identifies the local factors that existed at each study site and their variability between and within streams;
- determines which factors were most influential in controlling bank retreat rates;
- quantifies the effect of the dominant factors causing bank retreat; and

- produces models that describe how bank dimensions and stratigraphic types were related to variations in local bank characteristics, retreat rates and retreat types.

4.2 Methods

The methods used to meet the chapter aims are summarised in Figure 4.1. The study sites described in Section 2.4 were used for this study. Erosion rates and types were measured using repeated cross-profiling techniques outlined in Section 3.2.2.

4.2.1 Sediment characteristics

The bank stratigraphy at each study site was surveyed, mapped and described following McDonald *et al.* (1990). Sediment samples were collected from each stratum/sedimentary unit using a small hand-held corer and were stored in sealed bags for future analysis. For sedimentary units with larger cobble material, samples were taken using a larger corer. To ensure no disturbance was caused to the profile lines, the sedimentary units were traced laterally along the bank and sampled several metres away from the transect line. To determine the textural characteristics of each sedimentary unit, samples were dry-sieved following the methodology of Gordon *et al.* (2004) and Rowell (1994), using maximum and minimum sieve sizes of -2 ϕ and 4 ϕ respectively, with half-ϕ intervals between the intermediate sieves.

Sediment particles outside the maximum and minimum sieve restrictions were dealt with separately. Particles larger than -3 ϕ were measured individually and separated into their appropriate size class and then each size class was weighed. The hydrometer method was used to separate silt and clay particles that passed through the 4 ϕ sieve after the completion of dry sieving (Jones 2001). Following sediment analysis, data was entered into the *Gradistat Version 4.0* program for analysis of grain-size distribution (Blott 2000) to determine sediment texture, mode and median sediment size and the sediment sorting, skewness and kurtosis.

Thorne and Tovey (1981) noted that the retreat/stability of a bank is governed by the stratum with the largest sediment grain size. Others identify the toe sediment as a major influence on bank retreat and stability (Okagbue and Abam 1986). Thus, several general bank sediment descriptors were determined for future stratigraphic analysis. The stratum at each site with the largest median particle size was recorded (maximum median sediment size – median sediment is the most representative of actual sediment sizes – Gordon *et al.* 2004). The largest maximum particle size for each site was calculated in a similar fashion. A median sediment size below 3.0 m was also recorded for each site for future analysis of basal sediment control of retreat.

1. HOW DO THE LOCAL VARIABLES VARY WITHIN STREAMS?

Approach:
- Sediment/Stratigraphy – bank sedimentary units surveyed & analysed for texture, sediment components & descriptive statistics
- Bank geometry – measured from cross-sections
- Curvature – measured from plan form & aerial photography
- Hydrological characteristics – from discharge &/or rainfall data (Section 3.2.3)
- Community vegetation characteristics – tree density, tree height, DBH
- Root characteristics – root density measured using the profile-wall methodology
- Within-stream variation – means, coefficient of variation & direct observations

2. HOW DID THESE PARAMETERS VARY BETWEEN STREAMS?

Approach:
- Between-stream variation – ANOVA & *post hoc* Tukey's tests to compare streams

3. WHICH FACTORS WERE MOST INFLUENTIAL IN CONTROLLING BANK RETREAT?

Approach:
- PCA used to identify local factors that group with bank retreat
- Regression of variables with PCA axis
- Regressions between variables & bank retreat to identify factors most related to bank retreat.

4. QUANTIFICATION OF EFFECTS OF BANK RETREAT DRIVING FORCES – WHY IS THERE VARIABILITY?

Approach:
- Investigation of bank retreat thresholds – comparison by ANOVA of groups of sites separated by thresholds
- Cause of variability – ANOVAs between these groups to identify major determinant(s) of bank retreat variability
- Cause of bank angle variability – Regressions between bank angle & local bank characteristics to identify likely causes

5. DO DIFFERENT BANK TYPES EXIST & DO THEY DIFFER IN BANK CHARACTERISTICS &/OR RETREAT RATE?

Approach:
- Identification of bank types – Stratigraphy used to categorise banks. ANOVA & MRPP used to identify differences in bank geometry
- Bank type & retreat rate – ANOVA & MRPP used to identify differences in local bank features & retreat rates. Error plots & *post hoc* Tukey's tests identified where differences lay
- Bank types & retreat types – Box plots illustrated frequency of bank retreat types for the each bank type

Figure 4.1 – Summary of the approach taken to address the aims of Chapter 4.

4.2.2 Bank, channel and hydrological characteristics

Bank height was established using topographic surveys (Section 3.2.1). In many studies, bankfull or absolute bank height is used as representative of the eroding bank height (Hickin and Nanson 1984, Ponce 1978), but in this study, a more effective bank height – exposed bank height – was used. Gradually sloping upper bank sections were excluded from height calculations. The exclusion of these sections enabled statistical analyses to focus on the section of bank most affected by the stream flow. It also removed the influence of gradually sloped bank-floodplain interfaces, which have little effect on overall streambank retreat. Thus, bank angle was measured as the actual angle of the exposed bank height, also established from the topographic surveys (Section 3.2.1). For the remainder of this thesis, 'exposed bank height' and 'exposed bank angle' will be referred to as simply bank height and bank angle. Bankfull width was measured according to Section 3.2.2. Curvature was calculated by using the planform measured during site surveys and from aerial photographs, following standard methods (curve radius r_m/channel width w_m) (Begin 1981, Hickin 1974). Hydrological characteristics (velocity, discharge, specific stream power) were calculated for each site using the methodology outlined in Section 3.2.3.

4.2.3 Community vegetation characteristics

The analysis of retreat rate incorporated community vegetation characteristics to determine whether they had any influence on bank stability. Canopy, middle storey and ground cover density measurements were recorded (McDonald *et al.* 1990). For canopy and middle storey measurements, individual trees that were within a 10 × 10 m quadrat were counted. Trees with branching trunks or stems were counted as single trees. In locations where the width of the riparian vegetation was less than 10 metres, density calculations only considered the area up to and including the trees furthest from the bank edge. For example, if the bank vegetation only extended 6.0 m up the bank, a sample area of 6 × 10 m rather than 10 × 10 m was used. Ground cover was measured following McDonald *et al.* (1990). In conjunction with density measurements, the dominant species present at each site were recorded for all vegetation levels.

Individual tree heights and diameters at breast height (DBH) were recorded at each site for later comparisons with root morphology and retreat rates. A standard 'breast height' of 1.3 m was used and trees with branching trunks/stems were measured according to the guidelines established by Australian Greenhouse Office (2001) and U.S. Department of Agriculture 2003. Tree heights were measured using a clinometer.

4.2.4 Root characteristics

Methods for studying roots vary greatly according to the characteristics and level of accuracy required (Böhm 1979). Methods range from very destructive excavation and monolith techniques to the less intrusive profiling, glass walls and radioactive tracers. A profile wall methodology, described below, was chosen for this study as it provides quick and uncomplicated measurement of root density and can be adapted for use at the interface between the bank and channel.

Profile wall method and root area ratio

Root area ratio (RAR) is effectively the sum of the cross-sectional area of the roots intersected by a profile wall divided by the area of the wall. It gives a good indication of the density of roots at the streambank face. The profile wall method was used to measure RAR. This method is ideal to study soil and root profiles, especially when comparing results from different sites (Böhm 1979, Abernethy 1999, Riestenberg 1994, Shields and Gray 1992). However, this study was unusual in that RAR was measured at the bank-channel interface as the focus was on the interaction between roots and in-channel processes. Therefore, only shaping of profile walls down the bank was required rather than excavation of trenches. Initial rough profiles were shaped using a spade to provide access to the roots. These profiles were approximately 0.7 m wide and sampled the full bank height. The profiles were cleaned using water squirters and trowels to produce a clean, vertical profile wall. The wall was generally dug parallel to vertical banks, 0.05-0.1 m in from the edge, but for acute-angled banks, step profiles were dug at approximate 0.5 m intervals down the bank to ensure that RAR was measured adjacent to the bank edge (Figure 4.2).

Following the construction of the walls, roots were mapped using a 0.6 × 0.6 m clear Perspex clipboard overlayed by a clear laminate sheet. A 0.5 × 0.5 m square was etched and drawn on the Perspex sheet to identify the sample area. The clipboard was attached to the profile wall with four large screws to ensure it remained in place during mapping, and the laminate sheeting was temporarily fixed in place using water-resistant adhesive tape.

At each site, roots were mapped at intervals of about 0.5 m down the bank to the bank toe or until roots were absent. A new laminate sheet was used for each position down the profile. Roots intersecting the profile wall were mapped on the laminate sheet using a permanent marker. Roots that did not intersect perpendicular to the wall were mapped according to the area that intersected the wall as they still contribute to bank protection against flow (Böhm 1979).

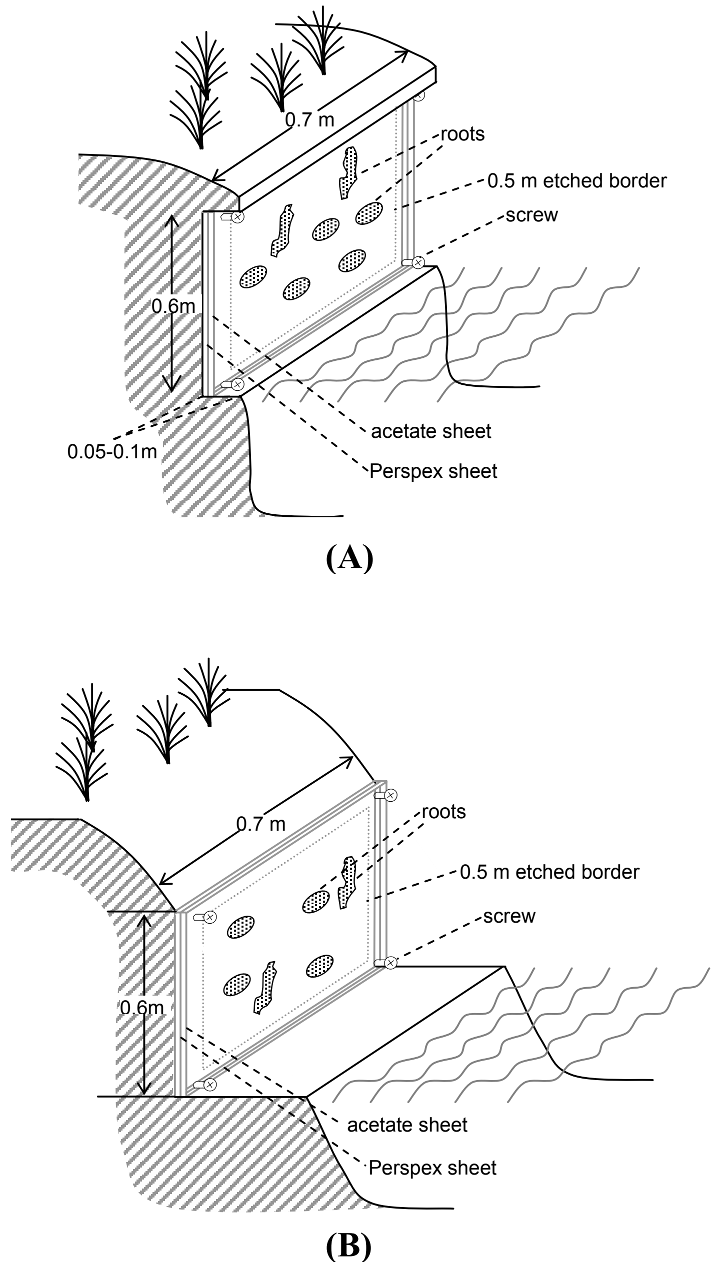


Figure 4.2 – Method for mapping root area ratio at the bank-channel interface on (A) a vertical bank; and (B) more acute-angled bank. These profiles were repeated as necessary to encompass the entire bank face.

As this study focussed on the link between root characteristics and bank retreat rather than on geotechnical considerations, no other root characteristics were required, because:

- variation in root density and morphology amongst species and communities are considered to have a greater impression on bank stability and bank retreat than inter-species differences in the root tensile strength (Abernethy 1999); this relationship between community root densities and bank retreat rates was tested in this study;
- data in this study were collected at the bank where roots were from a variety of species and a variety of individuals located at different distances from the bank edge. Hence, the effect on bank stability was a combination of root strengths provided by individuals of various species (i.e. the vegetation community). Although different species can have different root strengths and so influence bank stability differently (e.g. Riestenberg 1994), many studies have shown that strengths vary little between and within species (e.g. Abernethy and Rutherfurd 2001) and any differences that are present in root strengths can often be ignored. For example, Simon and Collison (2002) showed that root strength varied amongst several species, but that these strength differences were less important to bank stability than root area. Thus, interspecies differences in root properties were not investigated; and
- the cohesion offered by roots is believed to vary according to depth and the distance away from the stem (Abernethy 1999). As it would be impossible to isolate and identify roots of different individual trees without complete excavation, this variable was largely ignored, consistent with the main point of the study to examine riparian vegetation community contributions to reducing streambank retreat.

<u>Root area ratio (RAR) values</u>

RAR values at 1.0 m, 2.0 m and 3.0 m depth were measured, and a site average calculated, to determine whether RAR at different depths played different roles in influencing streambank retreat. More detailed examination of the relationship between erosion and RAR is presented in Chapter 5.

4.2.5 Bank types, sediment and bank retreat

Stratigraphic characteristics were used to categorise all study banks (Dapporto *et al.* 2003, Thorne and Tovey 1981) to determine whether banks of obviously different characteristics were subject to different rates of bank retreat. Banks were categorised according to the number of strata they had and the arrangement of these strata in the bank.

4.2.6 Statistical analyses

Multivariate relationships between potential retreat parameters and bank retreat rates were investigated with a Principle Components Analysis, which grouped parameters that were most strongly related to bank retreat. A multivariate approach is appropriate as it is likely that more than one parameter influenced retreat. ANOVAs, regressions and scatter plots were used to identify the complex relationships between bank retreat rate and important parameters. ANOVA and MRPP (McCune and Mefford 1999) (see Section 2.2) were used to identify groupings in bank types with regard to sedimentology, stratigraphy, RAR and community vegetation characteristics and retreat rates. The application of these methods is described further with the relevant results.

4.3 Field results: identification of site variables

Figure 4.3 summarises the results for each of the chapter aims, as outlined in Figure 4.1.

4.3.1 Sedimentology

A total of 52 strata of five sedimentary units (clayey sand, silty sand, sand-silt-clay composite, sand, sand with gravel/cobble) were identified. Sand, silt and clay content of bank sediments varied considerably between sites (32-98% sand, 0-30% silt, 0-38% clay), but most sedimentary units contained more than 30% sand (Figure 4.4). Seventy-three percent of all sampled sedimentary units consisted of more than 70% sand, while approximately 54% were composed of more than 80% sand, with varying contents of silt and clay. Liverpool Creek flows through sedimentary units that had much higher sand content than Jarra or Thornton Creeks. Approximately 56%, 84% and 59% of the sedimentary units in the banks of Thornton, Liverpool and Jarra Creeks respectively, had greater than 70% sand content. These figures ignore the presence of larger material in the strata, notably the presence of gravel, cobbles and boulders more prevalent in the wet tropical streams. Three sites (of 14) in Thornton Creek, three (of 10) in Jarra Creek and seven (of 10) in Liverpool Creek had one sedimentary unit exposed in the streambank profile that contained particles larger than 2 mm (-1 ϕ).

4.3.2 Stratigraphy

Stratigraphy and sediment size at each site are illustrated in Figure 4.5. The majority of bank strata on the three study streams included high sand content, consistent with the sandy beds observed in all three streams and the granitic lithology of each catchment. Banks comprised one, two or three strata, which varied in texture between sand with gravel/cobble and clayey sand. The arrangement of these strata was variable, but the coarser sedimentary units were usually at the bank toe. Sediment size varied between study sites (Table 4.1), with site maxima ranging between 0.2 mm (2.32 ϕ) and 150 mm (-7.23 ϕ) ($\bar{x}$ = 21.5 mm; CV = 213%).

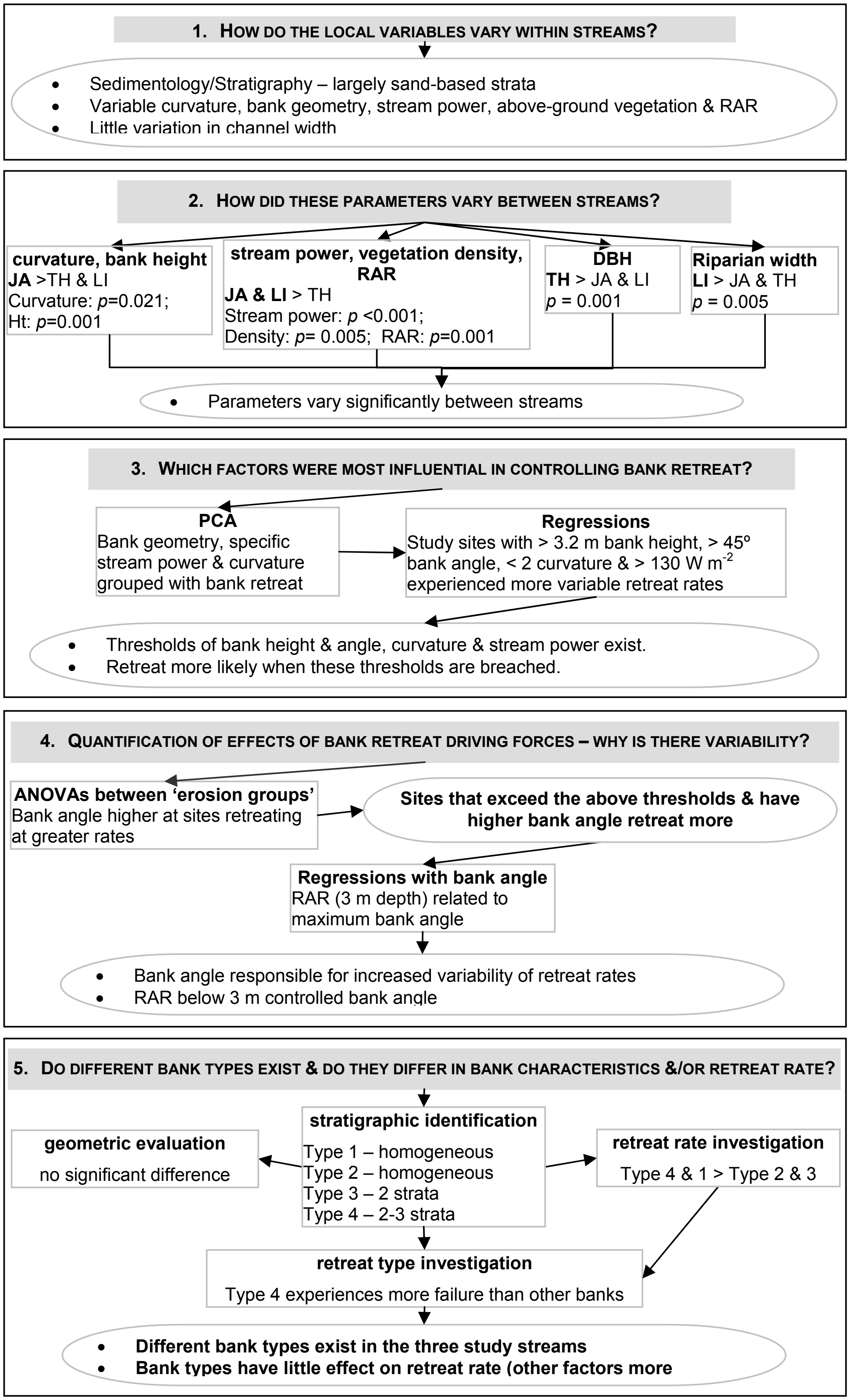


Figure 4.3 – Flowchart summarising the results relevant to each chapter aim, following the methodology outlined in Figure 4.1.

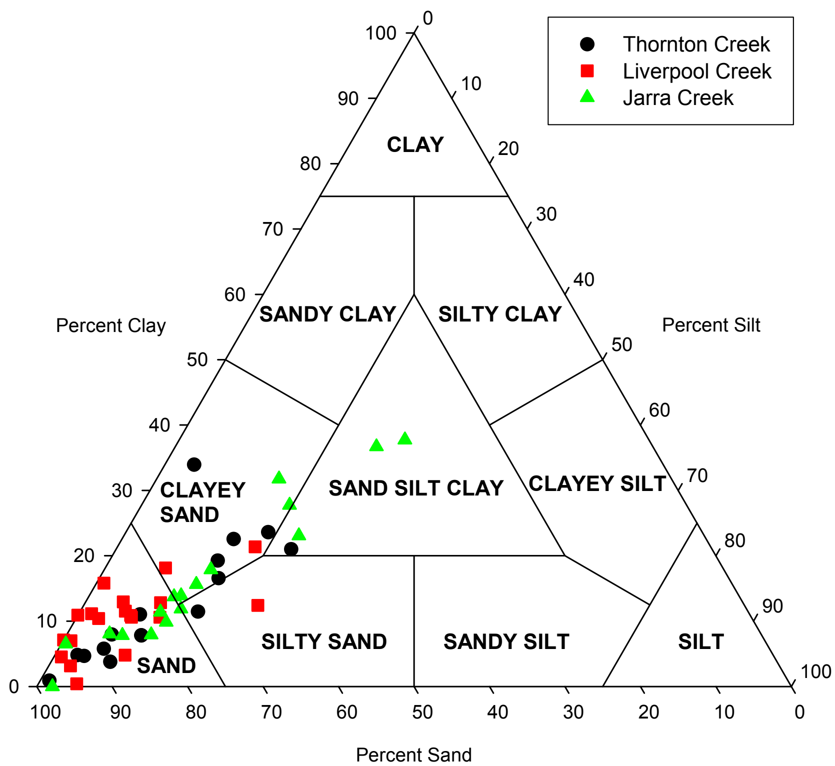


Figure 4.4 – Triangular texture diagram based on international fractions, illustrating the sand, silt and clay content of identified sedimentary units in the study streams (following Marshall 1947, 2003, Shepard 1954).

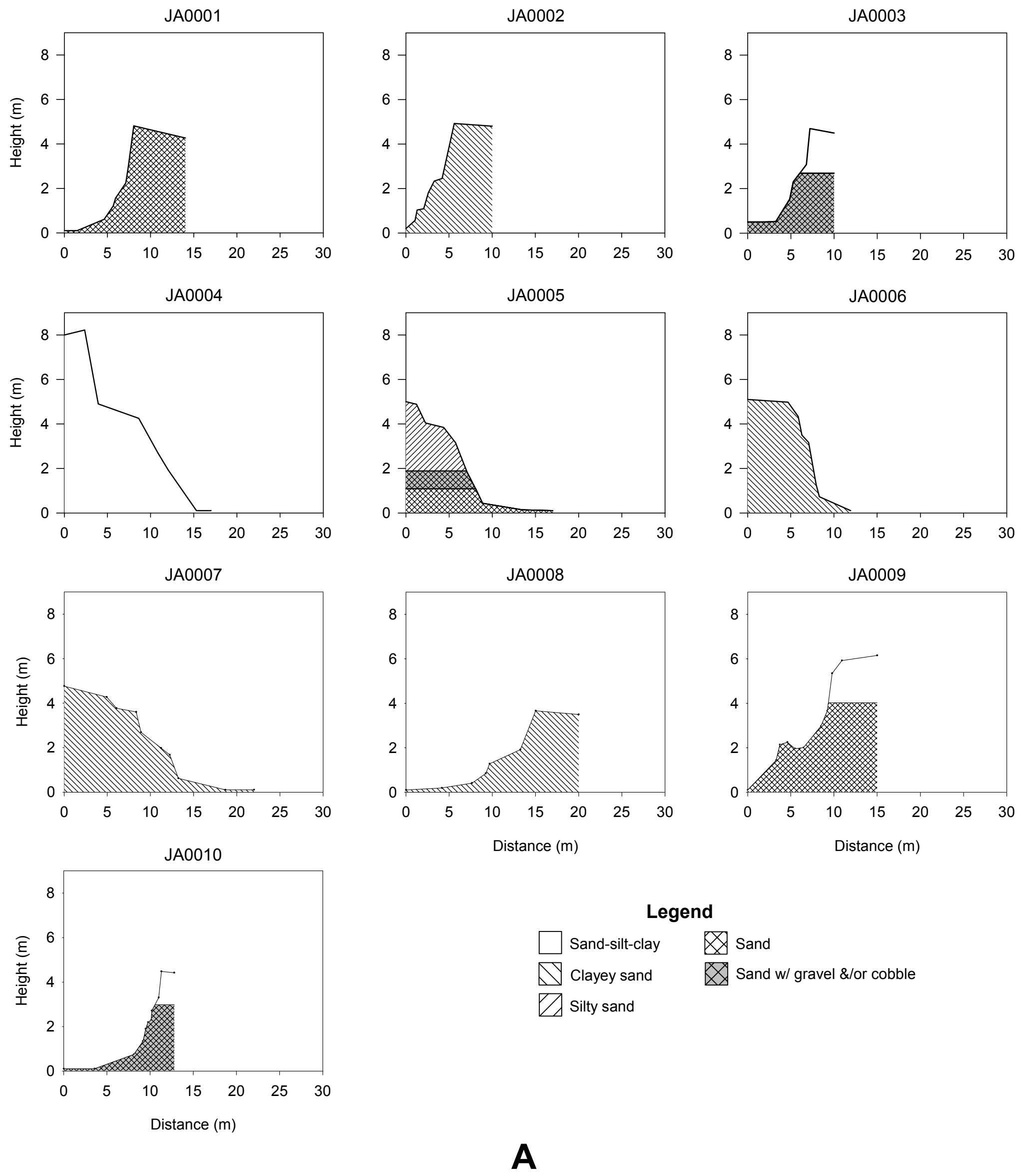


Figure 4.5 – Bank sedimentology of the eroding bank of study sites on (A) Jarra Creek, (B) Liverpool Creek and (C) Thornton Creek.

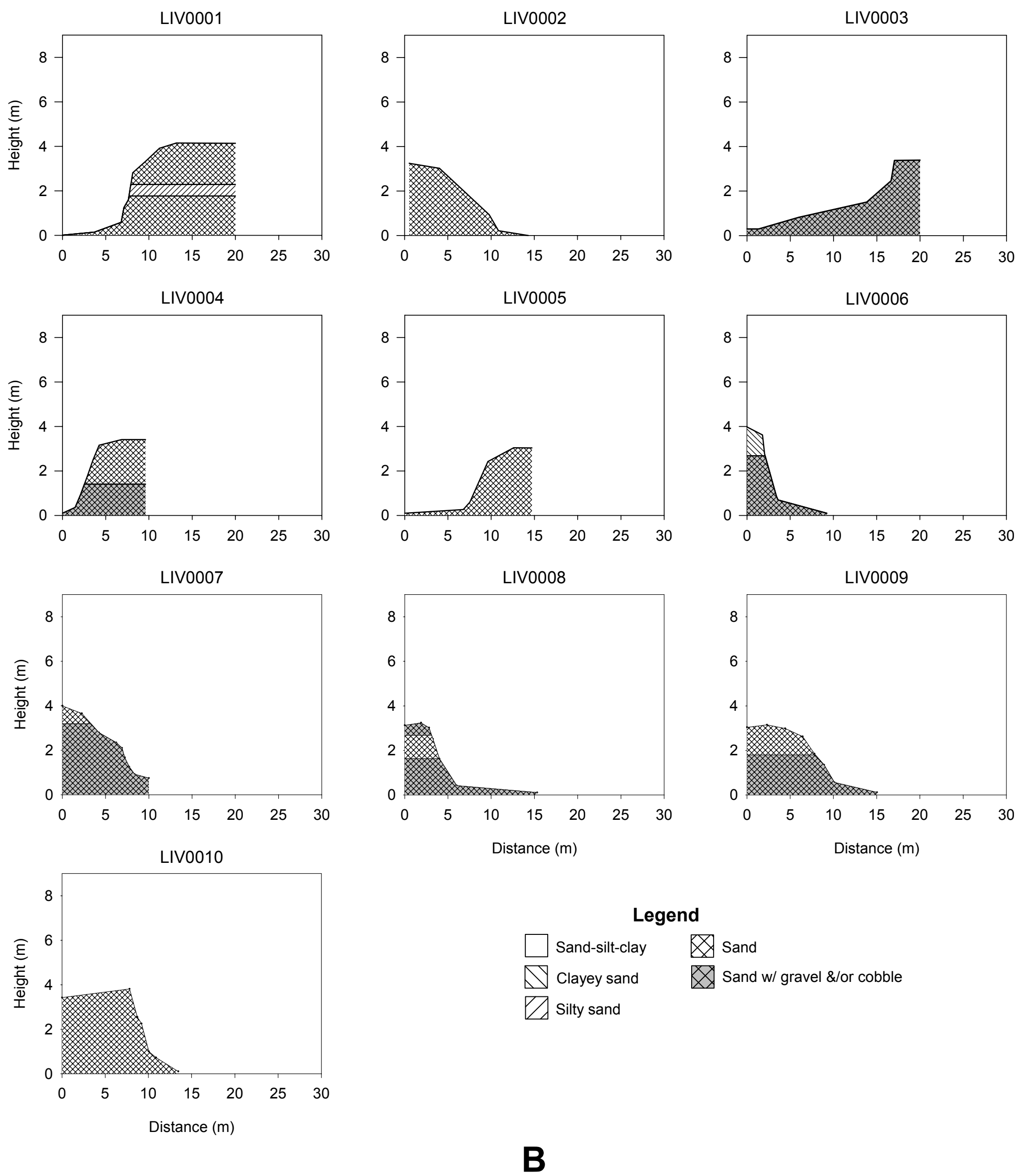


Figure 4.5 – continued. Bank sedimentology of the eroding bank of study sites on (B) Liverpool Creek.

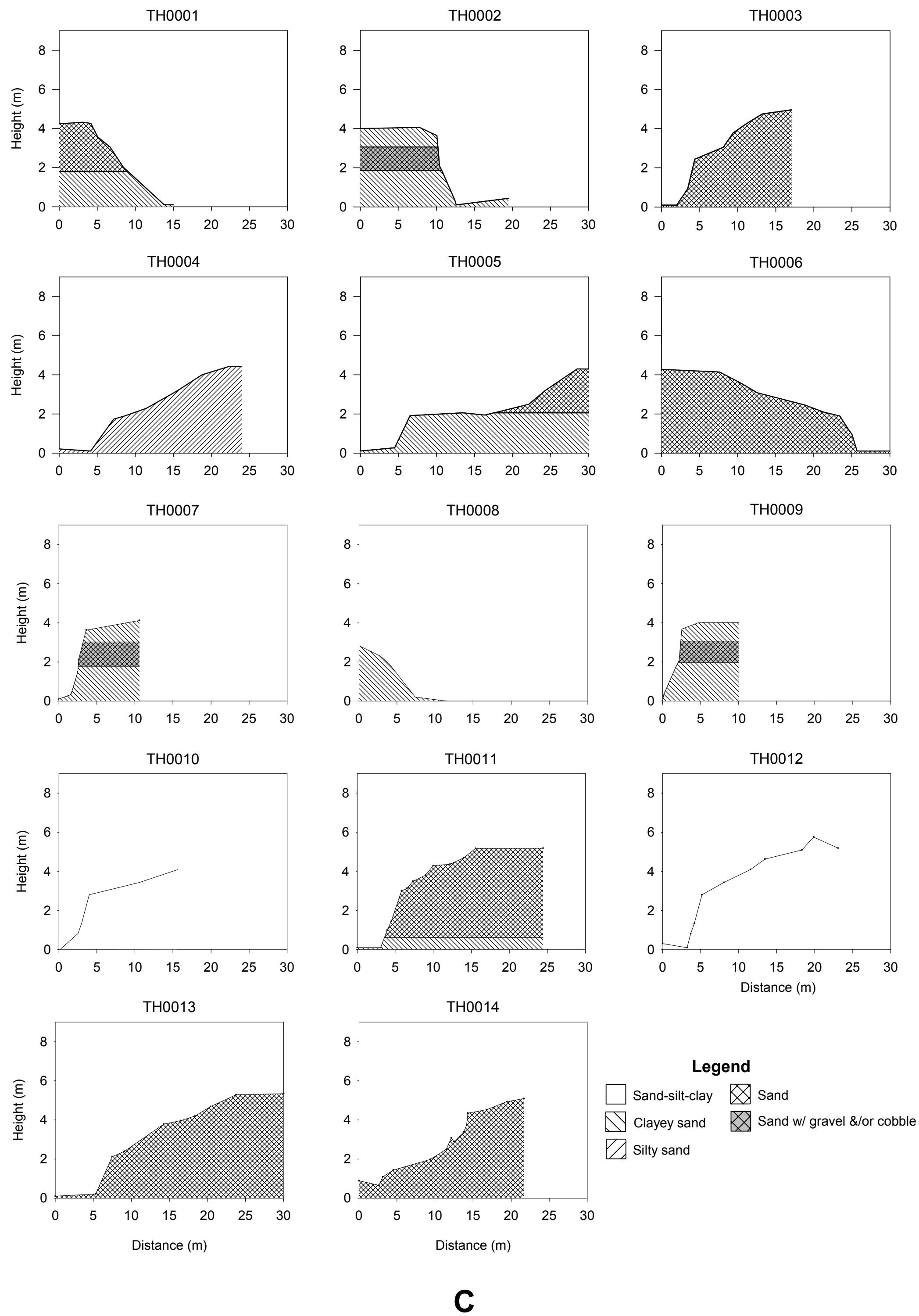


Figure 4.5 – continued. Bank sedimentology of the eroding bank of study sites on (C) Thornton Creek.

Table 4.1 – Study site sedimentary unit descriptions.

Site*	Stratum[†]	Height (m)	Sediment Type	Largest Sediment Size (mm)
JA0001	1	> 4.8	Sand	1.0
JA0002	1	> 4.9	Clayey sand	0.4
JA0003	1	2.0	Sand-silt-clay	4.0
	2	> 2.7	Sand & gravel	
JA0004	1	> 8.2	Clayey sand	0.2
JA0005	1	3.1	Silty sand	2.0
	2	0.8	Sand & gravel	
	3	> 1.0	Sand	
JA0006	1	> 5.1	Clayey sand	0.3
JA0007	1	> 4.7	Clayey sand	0.4
JA0008	1	> 3.6	Clayey sand	0.3
JA0009	1	2.13	Sand-silt-clay	0.4
	2	> 4.0	Sand	
JA0010	1	1.5	Sand-silt-clay	2.0
	2	> 3.0	Sand & gravel	
LI0001	1	1.86	Sand	0.6
	2	0.52	Silty sand	
	3	> 1.8	Sand	
LI0002	1	> 4.1	Sand	0.8
LI0003	1	> 3.4	Sand, gravel & cobble	150.0
LI0004	1	2.0	Sand	142.0
	2	>1.1	Sand, gravel & cobble	
LI0005	1	> 3.0	Sand	0.8
LI0006	1	1.3	Clayey sand	122.0
	2	> 2.7	Sand, gravel & cobble	
LI0007	1	0.8	Sand	111.0
	2	> 3.2	Sand (w/ gravel & cobble)	
LI0008	1	0.45	Sand, gravel & cobble	91.0
	2	1.15	Sand	
	3	> 1.6	Sand (w/ gravel)	
LI0009	1	1.35	Sand	83.0
	2	> 1.8	Sand, gravel & cobble	
LI0010	1	> 3.8	Sand	0.8
TH0001	1	2.51	Sand	0.4
	2	> 1.8	Clayey sand	
TH0002	1	1.0	Clayey sand	6.0
	2	1.2	Sand & gravel	
	3	> 1.8	Clayey sand	
TH0003	1	> 5.0	Sand	2.0
TH0004	1	> 4.4	Silty sand	0.3
TH0005	1	2.25	Sand	0.4
	2	> 2.05	Clayey sand	
TH0006	1	> 4.3	Sand	0.4
TH0007	1	1.1	Clayey sand	3.0
	2	1.25	Sand & gravel	
	3	> 1.65	Clayey sand	
TH0008	1	> 3.9	Clayey sand	0.3
TH0009	1	0.95	Clayey sand	2.0
	2	1.1	Sand & gravel	
	3	> 1.6	Clayey sand	
TH0010	1	> 4.4	Sand-silt-clay	0.4
TH0011	1	4.56	Sand	0.2
	2	0.6	Clayey sand	
TH0012	1	> 5.7	Sand-silt-clay	0.4
TH0013	1	> 5.3	Sand	0.6
TH0014	1	> 5.0	Sand	0.4

* Site codes: JA, Jarra Creek; LI, Liverpool Creek; TH, Thornton Creek
[†] Strata are numbered according to their position in the bank and do not correspond with similarly numbered sites on other banks.

4.3.3 Hydrologic, bank and planform characteristics

Curvature across all sites varied between 1.07 (more curved) and 4.86 (less curved) with a mean of 2.12; however, most sites had a curvature less than 2.0, with a few outliers exaggerating the mean (LI0007: 4.86; TH0001: 4.13; TH0002: 3.19; TH0011: 3.12). Mean curvature values were significantly lower (more curved) in Jarra Creek sites than Thornton Creek sites (ANOVA: $F_{2,31} = 4.4$, $p = 0.021$; Tukey's test: $p = 0.025$), but there was no significant difference between the curvature of sites on Liverpool Creek and those on either Jarra Creek or Thornton Creek (Tukey's test: LI-JA $p = 0.06$ LI-TH $p = 0.98$). Exposed bank height was generally constant, with a mean exposed bank height of 3.1 m, with all banks being within two standard deviations of the mean, ranging between 1.7 m and 4.4 m. There were, however, significant differences between the bank heights of Jarra Creek and both Liverpool Creek and Thornton Creek (ANOVA: $F_{2,31} = 9.74$, $p = 0.001$; Tukey's test: Jarra Creek – Liverpool Creek $p = 0.001$, Jarra Creek – Thornton Creek $p = 0.003$).

Bank angle was variable between sites, ranging between 22.6° and 64.5°, (mean of 41.9 ± 1.9° SE – Table 4.2). Mean channel width for all sites was 61.1 m and varied little (SE = 2.99 m). No significant differences were evident between streams for bank angle or channel width. Specific stream power varied between sites (overall mean of W m^{-2} = 128.0, minimum = 38.5, maximum = 280.8). There were significant differences in specific stream power (ANOVA: $F_{2,31} = 50.62$, $p < 0.001$) between Jarra Creek and Liverpool Creek (Tukey's test: $p < 0.022$), Jarra Creek and Thornton Creek (Tukey's test: $p < 0.001$) and Liverpool Creek and Thornton Creek (Tukey's test: $p < 0.001$), reflecting the different hydrologic regimes, roughness and channel capacity of the three streams.

4.3.4 Above-ground vegetation characteristics

Tree density varied greatly from 0 individuals in a 10 × 10 m quadrat at most disturbed sites to 33 in the same-sized quadrat in the more densely vegetated wet tropical sites. The presence of saplings in vegetated sites provided even greater riparian density. Most sites without trees were inhabited by dense ground cover (> 80%), largely comprising para grass (*Brachiara mutica*), guinea grass (*Panicum maximum*) and elephant grass (*Pennistum purpureum*) in the wet tropical sites and ribbon grass (*Chrysopogon fallax*) and black speargrass (*Heteropogon contortus*) in the wet-dry tropical sites. The sites on Jarra Creek and Liverpool Creek had the most dense bank vegetation, with the vegetated sites averaging 20.2 (± SE 3.7) and 19.1 (± SE 2.6) individuals in a 10 × 10 m quadrat respectively; in contrast, the vegetation density at Thornton Creek was significantly less, averaging 8.4 trees (± SE 0.9) in a 10 × 10 m quadrat (Tables 4.3 and 4.4).

Table 4.2 – Site hydro-geomorphologic characteristics

Site	Curvature (r_m/w_m)	Exposed Bank Height (m)	Exposed Bank Angle (°)	Width (m)	Specific Stream Power (W m^{-2})
JA0001	1.07	4.20	50.8	101.2	247.5
JA0002	1.37	4.35	43.9	79.1	280.8
JA0003	1.28	4.18	46.7	97.9	193.8
JA0004	1.13	3.33	64.5	55.5	267.0
JA0005	2.54	3.40	37.1	37.7	235.3
JA0006	1.54	4.25	49.4	62.1	135.8
JA0007	1.72	3.65	25.5	55.8	166.0
JA0008	1.92	3.25	44.5	48.0	229.0
JA0009	1.36	3.92	41.3	67.8	178.0
JA0010	1.10	3.74	49.6	83.8	149.4
Mean±SE	1.50±0.14	3.83±0.13	45.3±3.2	68.9±6.7	208.3±16.0
LI0001	2.25	2.24	59.5	39.6	225.2
LI0002	2.28	1.97	32.0	49.8	157.6
LI0003	1.84	1.86	30.3	54.5	144.0
LI0004	1.31	2.80	45.3	45.5	172.3
LI0005	1.75	2.78	37.1	34.0	230.5
LI0006	2.74	2.91	58.4	37.4	211.0
LI0007	4.86	3.07	33.7	50.6	156.0
LI0008	2.62	2.82	34.3	94.0	84.0
LI0009	2.75	2.59	35.4	89.4	88.4
LI0010	1.14	3.81	34.0	80.4	110.6
Mean±SE	2.35±0.33	2.69±0.18	40.0±3.4	57.5±7.0	158.0±16.9
TH0001	4.13	3.06	23.3	50.1	54.6
TH0002	3.19	3.54	54.5	63.3	43.3
TH0003	2.06	2.44	45.9	53.9	50.8
TH0004	1.89	1.91	22.6	58.9	46.6
TH0005	2.42	1.78	41.5	54.5	50.4
TH0006	2.88	2.47	40.0	63.8	43.1
TH0007	1.60	3.29	58.7	63.2	45.7
TH0008	1.71	1.70	26.4	65.0	44.4
TH0009	1.72	3.68	55.4	57.0	50.6
TH0010	2.51	2.80	36.2	56.8	50.8
TH0011	3.12	3.80	47.5	45.7	63.0
TH0012	2.54	2.80	55.4	56.1	51.2
TH0013	2.78	3.79	30.1	51.2	56.2
TH0014	1.24	3.69	33.1	74.8	38.5
Mean±SE	2.41±0.25	2.91±0.24	40.8±4.0	58.2±2.4	49.2±2.0
Overall Mean±SE	**2.13±0.15**	**3.11±0.13**	**41.9±1.9**	**61.1±3.0**	**128.0±13.7**

Table 4.3 – Results of ANOVA on four vegetation characteristics between the three study streams (df = 2, 16), showing their variability between streams.

Statistic	Density	Riparian Width	DBH	RAR
F-value	7.386	7.412	12.405	10.393
***p*-value**	0.005	0.005	0.001	0.001

Table 4.4 – Results of *post hoc* Tukey's tests (*p*-values) on four vegetation characteristics for the three study streams identifying where stream differences lay. Significant contrasts (*p* < 0.05) are highlighted.

Streams*	Density			Width			DBH			RAR		
	Ja	Li	Th	Ja	Li	Th	Ja	Li	Th	Ja	Li	Th
Jarra Creek	–	0.953	**0.012**	–	**0.026**	0.934	–	0.169	**0.046**	–	0.207	**0.001**
Liverpool Creek	0.953	–	**0.013**	**0.026**	–	**0.007**	0.169	–	**0.0004**	0.207	–	**0.026**
Thornton Creek	**0.012**	**0.013**	–	0.934	**0.007**	–	**0.046**	**0.0004**	–	**0.001**	**0.026**	–

* Stream codes: Jarra Creek = Jarra Creek; Li = Liverpool Creek; Th = Thornton Creek

Riparian widths followed different trends, with vegetated Liverpool Creek sites having much wider riparian strips ($\bar{x}$ = 24.9 m ± SE 6.8) than either Jarra Creek ($\bar{x}$ = 6.0 m ± 1.0) or Thornton Creek (3.7 m ± 0.4) (Tables 4.3 and 4.4). Trees at Thornton Creek, however, had significantly greater trunk girths (diameter at breast height $\bar{x}$ = 0.86 m ± 0.06) than Liverpool Creek ($\bar{x}$ = 0.47 m ± 0.04) or Jarra Creek ($\bar{x}$ = 0.6 m ± 0.08), reflecting the larger species of woodland trees that inhabited the drier sites.

4.3.5 Root characteristics

RARs at the wet tropical study sites were significantly greater than at the wet-dry tropical sites (Tables 4.3 and 4.4). The ANOVA and Tukey's tests showed no significant difference between the RARs of sites in Liverpool Creek and Jarra Creek; however, Thornton Creek sites had significantly lower RARs at the bank-channel interface than either of the wet tropical streams.

4.4 Analysis of field results: quantification of bank retreat driving forces

4.4.1 Identification of variables related to bank retreat

A principle components analysis (PCA) was conducted on the suite of local variables to determine which local factors grouped with retreat rates and types. The variables used included all vegetation characteristics (density, width, RAR at different depths etc.), sediment size (site maximum d_{50}, site d_{50} below 3.0 m depth), bank height, bank angle, specific stream power, channel width, curvature and bank retreat rates (Sections 3.2.2 and 4.2). Scatter plots were used to explore the relationships between bank retreat rates and the important characteristics suggested by the PCA and regressions were performed to quantify these relationships.

The PCA identified vegetation characteristics and, to a lesser degree, sediment size, as the major contributors to variation between sites along Axis 1 (Figure 4.6, Table 4.5). Axis 1 groupings will be discussed further in Section 4.4.2, in relation to causes of variability within bank retreat driving variables. On Axis 2, increasing bank retreat was grouped with increasing bank angle, specific stream power and exposed bank height and decreasing curvature (Figure 4.6, Table 4.5). Regressions of these variables with PCA Axis 2 explain their grouping along this axis in more detail, with moderate relationships ($r^2 = 0.377\text{-}0.48$) between all these variables and Axis 2 (Figure 4.7). There was demarcation between Jarra Creek and the other streams along this axis, suggesting that the bank angle, bank height, specific stream power and curvature influenced the rate of bank retreat at Jarra Creek study sites differently from other sites.

Regressions between bank retreat rate and the variables grouped with retreat rate by the PCA did not identify further relationships (Figure 4.8). However, Figure 4.8 shows that bank retreat rates were generally low; and particular study sites, within certain limits of the variables identified in the PCA, had more variable and less predictable bank retreat rates. Those sites had curvatures between 1 and 2, bank heights greater than 3.2 m, bank angles greater than about 45° and specific stream power greater than 130 W m^{-2} (Figure 4.8). An outlier (TH0009) was noticeable in the specific stream power – bank retreat rate regression. Removing this outlier from the regression had little impact on the value of r^2 and can be ignored. No noticeable pattern was observed in bank retreat rates with regards to discharge, specific stream power or bankfull width.

Thus, the local factors that most influenced bank retreat at the majority of sites were curvature, bank height, bank angle and specific stream power – locations with low curvature, high exposed bank heights, high bank angle and high specific stream power retreated at greater rates.

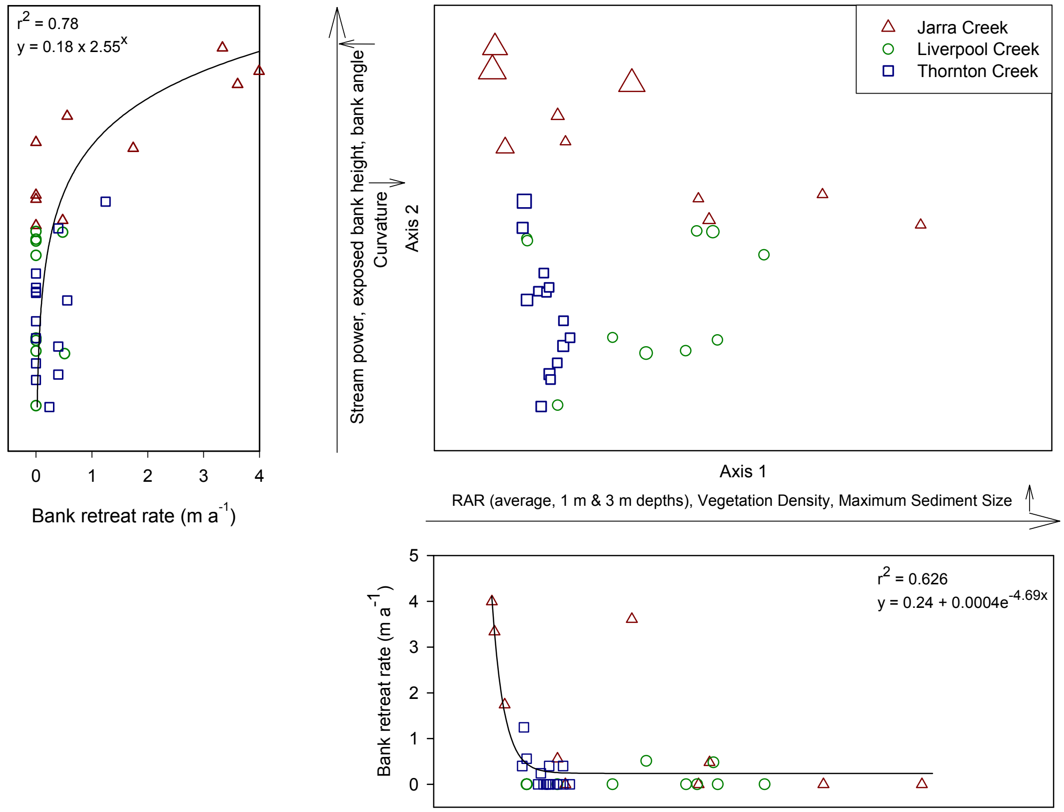


Figure 4.6 – Results of a PCA on hydrological, geomorphological and vegetative characteristics of study sites.

The plots below and to the left of the main plot illustrate relationships between bank retreat rate and the corresponding axis. For the main plot, the variables that correlated strongly with each axis are listed, and the symbol size is proportional to the bank retreat rate. The r^2-value and regression equation are indicated in the side plots.

Table 4.5 – Major correlates with Axes 1 and 2 in the PCA illustrated in Figure 4.6.

Variable	Axis	
	1	2
RAR (average)	**0.5272**	0.1206
Vegetation density	**0.4956**	-0.0030
RAR (1.0 m depth)	**0.4723**	0.0421
RAR (3 m depth)	**0.3533**	0.0268
Maximum sediment size	**0.1979**	-0.1820
Exposed bank height	-0.0142	**0.4624**
Curvature	-0.0174	**-0.4465**
Specific stream power	0.1888	**0.4270**
Bank angle	-0.1495	**0.4098**
Retreat rate	-0.1760	**0.4317**

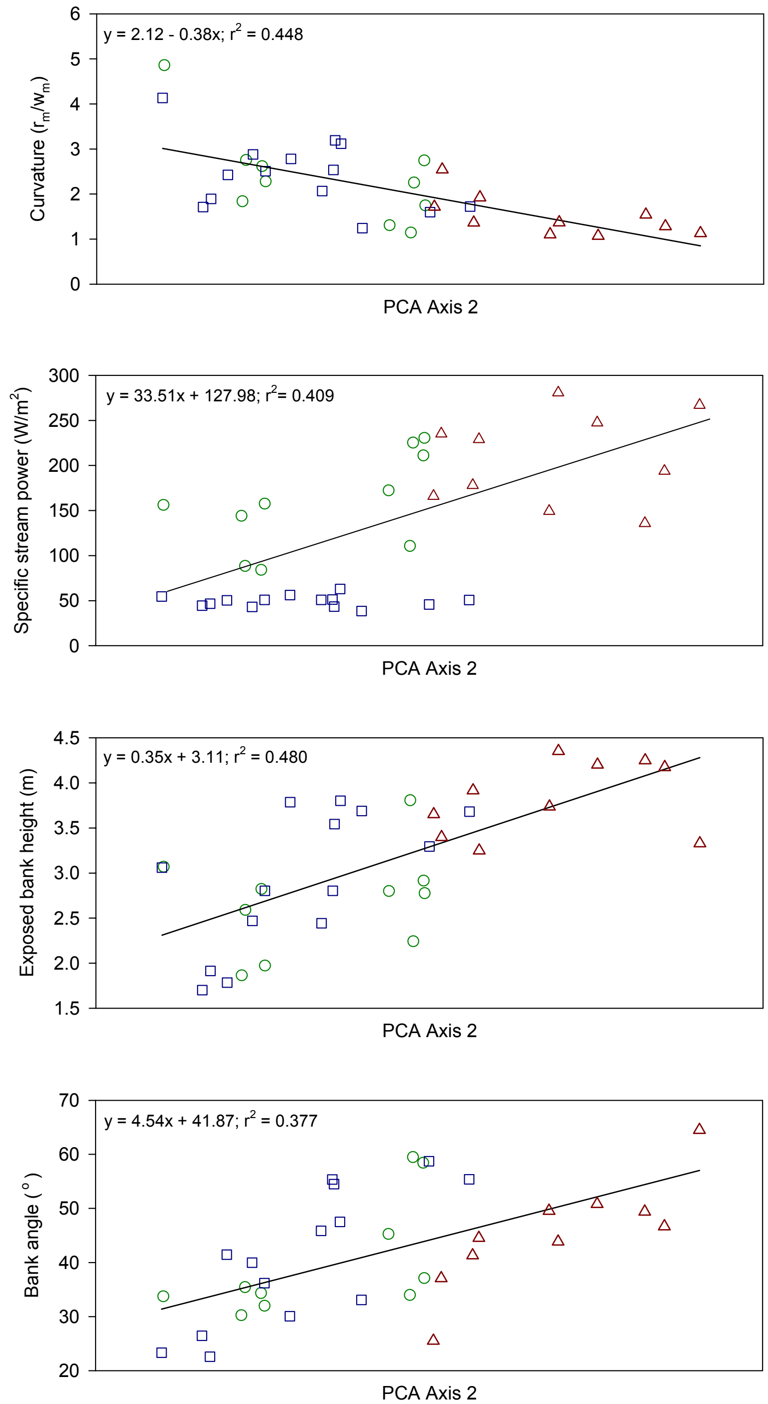


Figure 4.7 – Regressions of variables identified as contributors to bank retreat in the PCA (Axis 2). Symbols as in Figure 4.6.

The regression equations and the r^2 values are shown for each plot.

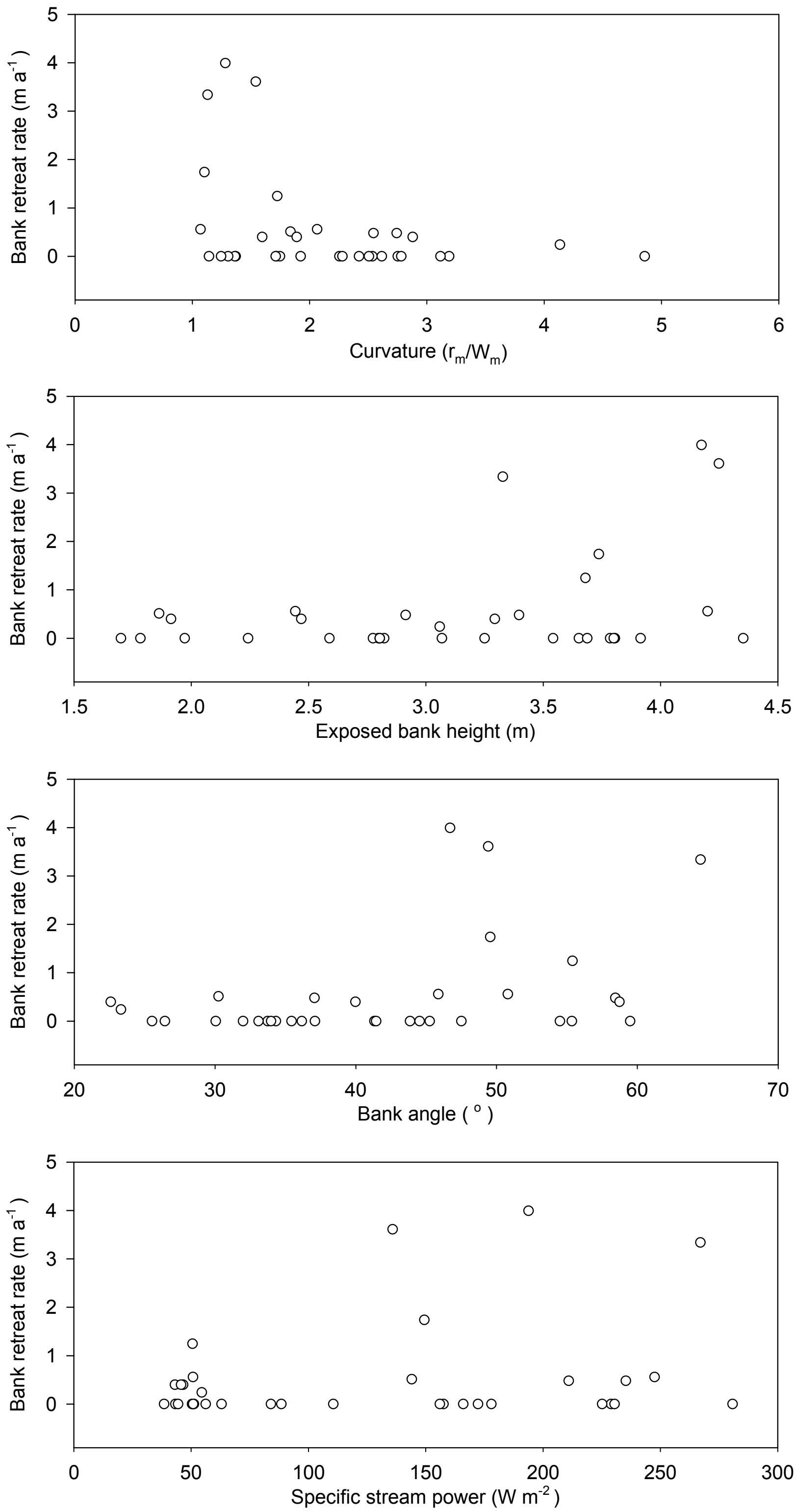


Figure 4.8 – Relationships between bank retreat rate and curvature, exposed bank height, bank angle and specific stream power.

4.4.2 Quantification of relationships between bank retreat and measured variables

Variability within bank retreat driving variables

To determine the cause of the bank retreat rate variability once thresholds of curvature, bank height, bank angle and specific stream power had been breached (Section 4.4.1 and Figure 4.8), each variable was investigated independently. For curvature, sites were assigned to 'erosion groups' based on the relationship between their bank retreat and curvature. Because of the variability of bank retreat rates for curvature values less than two, three 'erosion groups' were established, with group 1 comprising sites with curvature less than 2.0 and bank retreat rates of more than 1.0 m a^{-1}, group 2 comprising sites with a curvature of less than 2.0 and bank retreat rates of less than 1.0 m a^{-1} and group 3 comprising those sites that had a curvature of more than 2.0 (Figure 4.9). An ANOVA confirmed that group 1 moved at significantly different rates from groups 2 and 3 (ANOVA: $F_{2,\ 31} = 57.75$; $p < 0.001$; Tukey's test: p (1-2) < 0.001; p (1-3) < 0.001; p (2-3) = 1.0).

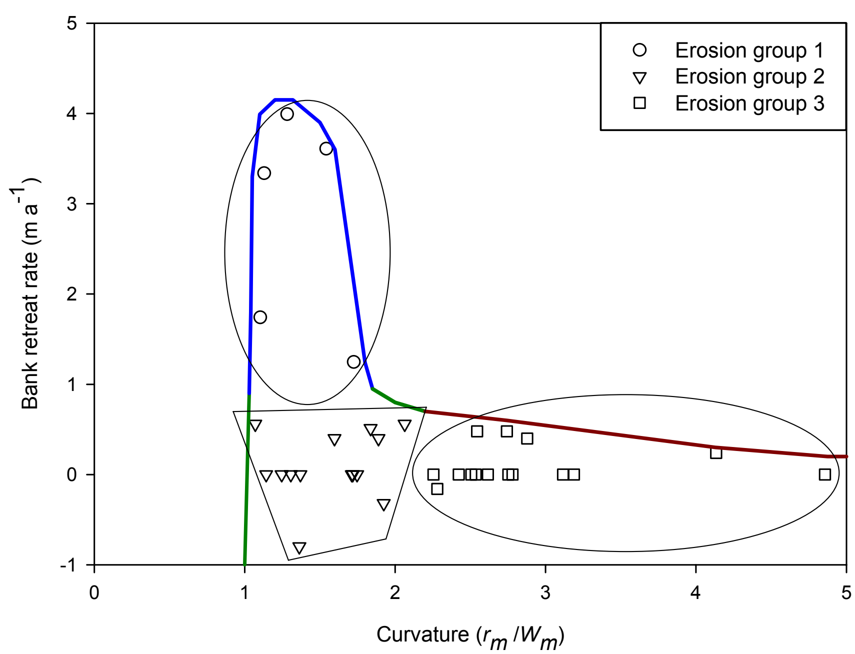


Figure 4.9 – Curvature-bank retreat rate relationship, showing the erosion groups identified (see text).

Similar demarcation between sites of erosion group 1 and groups 2 and 3 was evident in the relationships between bank retreat rate and bank height, bank angle and specific stream power. The highly mobile sites of group 1 (high curvature) all had greater specific stream powers, and bank heights and angles. ANOVAs were performed on each of the PCA-identified variables to determine if any of them could be responsible for this variation. The only significant variable (other than bank retreat rates) demarcating the groups was bank angle (Figure 4.10).

Thus, all the variables grouped with bank retreat by the PCA (curvature, bank height, bank angle, specific stream power) had some influence on bank retreat, but the variability of retreat rates was largely due to variations in bank angle – if the above thresholds had been satisfied, steep banks retreated faster than more gradual sloping banks.

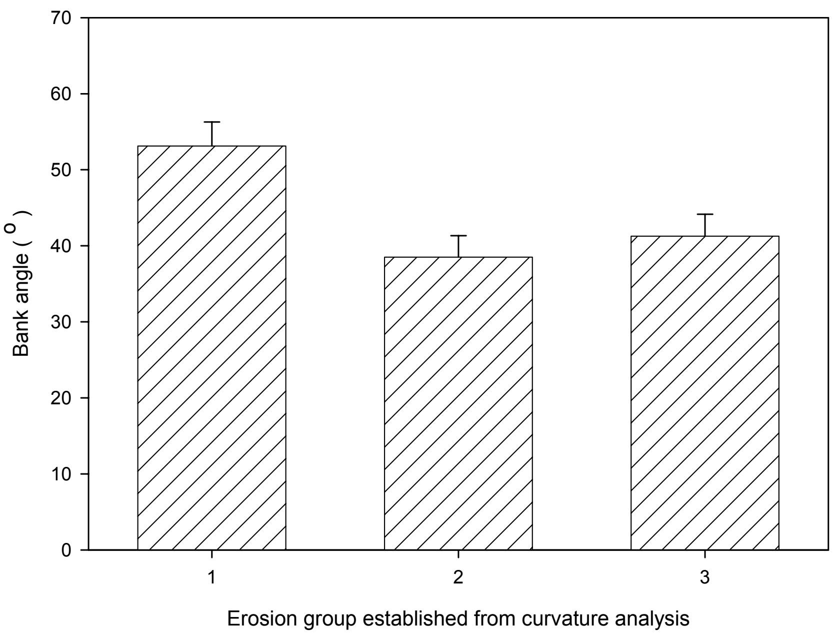


Figure 4.10 – Mean bank angle for erosion groups (from Figure 4.9), showing differences between erosion groups.
ANOVA: $F_{2,31} = 3.64$, $p = 0.038$; Tukey's tests: p (1-2) = 0.03; p (1-3) = 0.087; p (2-3) > 0.7.

Cause of variations in bank angle

The PCA also identified variability in sediment size, root area ratios and vegetation density in streams along Axis 1, separately from the other bank retreat-causing factors (Figure 4.6). All of these variables increased linearly with the Axis 1 scores; however, bank retreat rate decreased exponentially along this axis ($r^2 = 0.626$), suggesting that these vegetation and sediment variables have a strong negative influence on bank retreat – as sediment size, vegetation density and root density increase, bank retreat decreases exponentially. Thus, further investigation was undertaken to determine whether bank angle and bank retreat rate were related to sediment and vegetation characteristics and to determine the nature of these relationships.

Scatter plots of RAR measures and bank angle showed that mean RAR and RAR at a depth of 1.0 m were not related to bank angle. However, RAR at a depth of 3.0 m appeared to be related to maximum bank angle, which declined exponentially with increasing RAR (Figure 4.11). To examine this observation objectively, the RAR data were separated into groups and the maximum bank angle for each group was determined, as follows. All RAR values were sorted in an ascending logarithmic scale (this scale spread the lower values), then groups of values were delimited by the following steps in the RAR values: 0, 0.00009, 0.0003, 0.0006, 0.0009, 0.003, 0.006, 0.009, 0.03, 0.06 and 0.09 (Figure 4.12). Maximum bank angle within each group and its corresponding RAR value were identified and the regression was performed on those values. Groups without any representative values were ignored and values of zero were assigned to their own single group. The model showed that the relationship between maximum bank angle and RARs at a depth of 3.0 m followed a three-parameter exponential decay model (Figure 4.11). Thus, a variety of bank angles existed at low RARs, but as RAR increased, this variability decreased exponentially. So, regardless of other influential factors, banks occupied by sparse basal root networks were less likely to support steep slopes, indicating an indirect reliance of bank retreat on basal RAR.

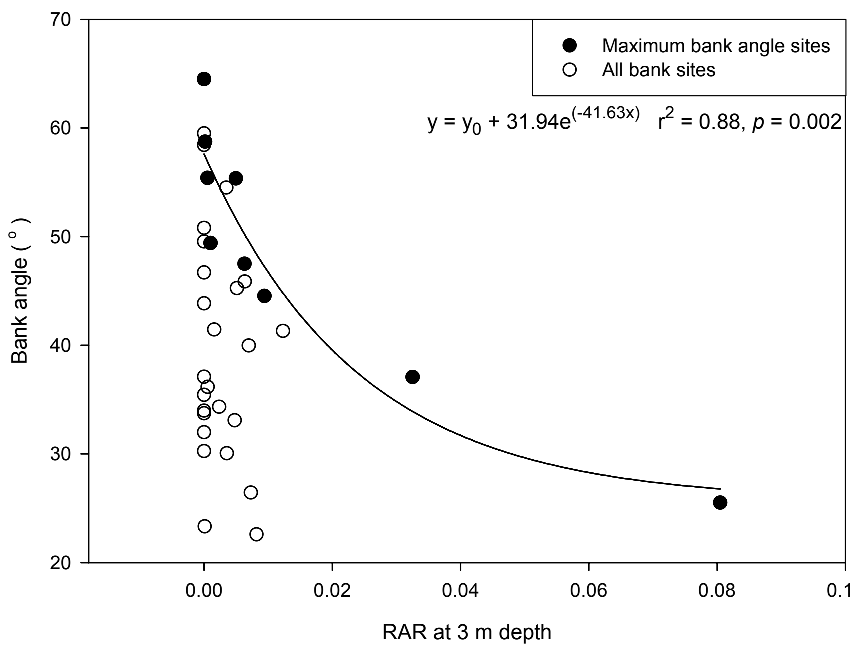


Figure 4.11 – Exponential decay relationship between RAR at 3.0 m depths and maximum bank angle for RAR groups.

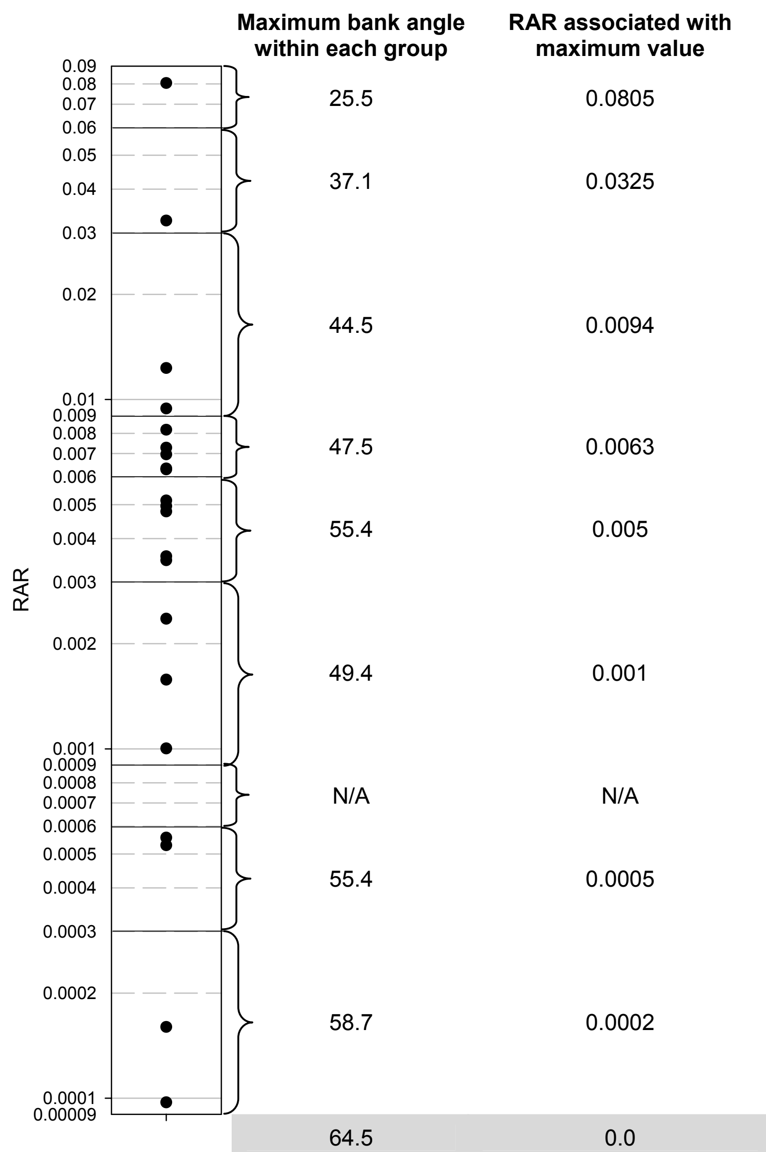


Figure 4.12 – RAR values on logarithmic scale, showing groups used to determine bank angle maxima through range of values.

Bank angle maxima and their corresponding RAR are also illustrated. Shaded section illustrates the initial grouping of RARs of zero value unable to be grouped on the logarithmic scale.

Simple three-dimensional scatter plots, correlations, and regressions of Axis 1 (RAR and sediment) against bank angle showed no relationships between sediment and bank angle. Nevertheless, an ANOVA and *post hoc* Tukey's tests separating sites into groups according to their median sediment size at depths greater than 3.0 m (1 – clay/silt; 2 – sand/gravel; 3 – cobble/boulders) suggest that sediment size accounted for some noise in RAR and thus, bank angle (ANOVA: $F_{2,31} = 2.727$; $p = 0.081$; Tukey's tests between sediment group 1 and 3: $p = 0.068$ – Table 4.6), irrespective of the considerable variation in RAR within each group. RARs increased with sediment size, suggesting that while sediment may become less cohesive and so less resistant to flow as particle size increases, this characteristic may be masked by the extra resistance offered by increased RAR. Similarly, in the PCA, RAR (3.0 m depth) and sediment size had a moderate ($r^2 = 0.393$) and weak ($r^2 = 0.123$) positive linear relationship with Axis 1 respectively (Figure 4.6).

Thus, bank angle explained much of the variance in retreat rates and was largely controlled by RAR below 3 m and, possibly, median sediment size below 3 m.

Table 4.6 – Results of *post hoc* Tukey's tests associated with an ANOVA of root area ratio (RAR) variation between sediment size groups. Figures shown in bold typeface indicate results of interest.

Sediment group	RAR at 3.0 m depth		Tukey's tests results on sediment groups*		
	Mean	SE	1	2	3
1	0.002	0.0008	–	0.848	**0.068**
2	0.005	0.0027	0.848	–	0.185
3	0.018	0.0128	**0.068**	0.185	–

* 1 = clay/silt; 2 = sand/gravel; 3 = cobbles/boulders

4.4.3 Stratigraphy, bank types, their features and influence on bank retreat

<u>Identification of bank types</u>

Bank stratigraphy was used to categorise banks. Four bank types were determined from these characteristics. Type 1 encompassed homogeneous banks that largely consisted of medium-grained sediments (sand-silt-clays/clayey sands/silty sands). Type 2 included homogeneous banks with coarse-grained sediments (sands). Types 3 consisted of heterogeneous banks, with two sedimentary units composed of medium to coarse-grained sandy material. Type 4 also consisted of heterogeneous banks composed of two to three sedimentary units, but with the lower stratum (of 2) or middle stratum (of 3) composed of sand-cobble (Table 4.7). Variation in bank angle and height existed within each bank type, but the mean angle and height of the different bank types reflected the stratigraphy. The homogeneous Bank Type 1 exhibited high, gradual sloping banks; Types 2 and 3 were generally low, gradual sloping banks, while Type 4 were high, steep banks (Figure 4.13).

Table 4.7 – Summary of bank type stratigraphic and geometric characteristics.

Bank type	Bank angle (º)	Bank height (m)	Number of strata	Texture
1	41.0	3.2	1	Medium grained
2	39.9	3.0	1	Coarse grained
3	38.4	3.1	2	Both medium to coarse grained
4	45.7	3.1	2-3	Lower strata coarse to very coarse grained

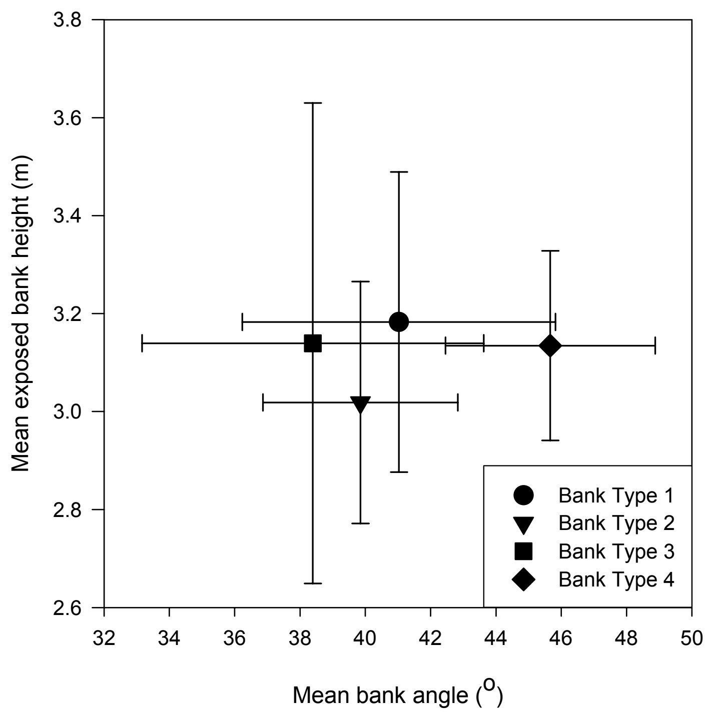


Figure 4.13 – Angle and height of the different bank types categorised from the study sites. Error bars represent standard error from the mean.

One-way ANOVA and MRPP (McCune and Mefford 1999) were used to identify any differences in bank angle and height between bank types. ANOVA was used to test angle and height separately, while MRPP was used to test any multivariate differences. Both nominal and rank transformed data were used in the comparison to compare real and directional relationships. Assumptions with regards to multivariate normality and homogeneity of variances are rarely met with hydro-geomorphological data, so MRPP is a better option than MANOVA in this case (McCune and Mefford 1999).

ANOVA and MRPP found no significant difference existed between bank types with regard to their bank angle and height (nominal & rank transformed) (Table 4.8). Specifically, the MRPP found more variation within groups than would be expected, thus reducing the effects of contrasts between groups (Figure 4.13). However, it also identified the heterogeneous Bank Type 4 as having noticeably larger mean bank angle than the other bank types. Further ANOVA and MRPP operations excluding Bank Type 1, probably the most variable with regard to bank angle, illustrate this more clearly. ANOVA and *post* hoc Tukey's tests show significant differences in bank angle between Bank Types 4 and 2 (ANOVA: $F_{2,22} = 3.62$, $p = 0.044$; Tukey's: $p = 0.041$) (Tables 4.9 and 4.10).

The results of these procedures indicate that while there is no correlation between height, angle and bank type, angles do differ between bank types, especially with regards to types 4 and 2.

Table 4.8 – ANOVA and MRPP results for bank type comparisons with regard to angle and height.

	ANOVA* Nominal Data		ANOVA* Rank Transformed		MRPP Nominal	MRPP Rank Transformed
	Angle	Height	Angle	Height		
F-Value/A-Value	0.648	0.074	0.601	0.113	-0.011	-0.006
Significance	0.591	0.974	0.619	0.952	0.53	0.49

* degrees of freedom = 3, 30

Table 4.9 – ANOVA and MRPP results for bank type comparisons with regard to angle and height, excluding Bank Type 1. Significant result shown in bold typeface.

	ANOVA*		MRPP
	Angle	Height	Nominal
F-value/A-value	3.619	1.191	0.009
Significance	**0.044**	0.323	0.344

* degrees of freedom = 2, 22

Table 4.10 – Results of *post hoc* Tukey's tests of bank angle between bank types, excluding Bank Type 1.

Bank Type	2	3	4
2	–	0.919	**0.041**
3	0.919	–	0.286
4	**0.041**	0.286	–

<u>Bank types and their effect on rates and types of bank retreat</u>

MRPP was used to identify any differences between the four bank types with regard to interrelationships between a suite of bank parameters, namely bank maximum median sediment size, median sediment size below 3.0 m depth (both chosen to reflect the importance of the largest sediment strata and the basal sediment type on bank stability) (Section 4.2.1), mean RAR and RAR at a depth of 3.0 m (to investigate the effect of basal RAR), vegetation density and overall bank retreat. It returned significant results ($p < 0.001$), indicating that the groups were significantly different in terms of one or several of the above parameters. Error plots of each of these variables and ANOVAs, where necessary, suggest where the inter-bank type differences lay (Figure 4.14). Bank Type 4 had larger sediments at depths greater than 3.0 m (ANOVA: $F_{3,30} = 7.71$, $p = 0.001$; Tukey's: Bank Types 4-1 $p = 0.003$, 4-2 $p = 0.002$, 4-3 $p = 0.024$). It also appeared that Bank Type 4 had very low RAR values at depths greater than 3.0 m, but the difference from other bank types was not significant (ANOVA: $F_{3,30} = 2.31$, $p = 0.096$). If there is a real difference, it is masked by the high variance of the other groups. Bank Types 2 and 3 had greater vegetation density and RAR values and experienced little bank retreat. Bank Type 1 was anomalous as it experienced similar bank retreat to Bank Type 4 but had smaller sediment size and greater RAR and vegetation density. However, bank retreat rates were highly variable within Bank Type 1. These results suggest that while differences in retreat rates existed between the different bank types, and these differences could be loosely connected with differences between the bank types with regard to their basal sediment and RAR attributes, the parameters in the preceding sections (curvature, specific stream power, bank height and angle) perhaps explain more of the variance in retreat rate.

The frequency of different erosion mechanisms varied between bank types. Interestingly, banks of the homogeneous bank types (1 and 2) retreated little (12 of 19 sites experienced no retreat). Scour was the dominant erosion process in these types of banks (3 incidences), but most banks of Type 3 were stable, with only one subject to scour. Bank Type 4 was exposed to more cantilever/slippage failures subsequent to scour of their basal coarse-grained sedimentary units (2/4 incidences). Figure 4.15 illustrates the frequencies of these bank erosion mechanisms for each bank type.

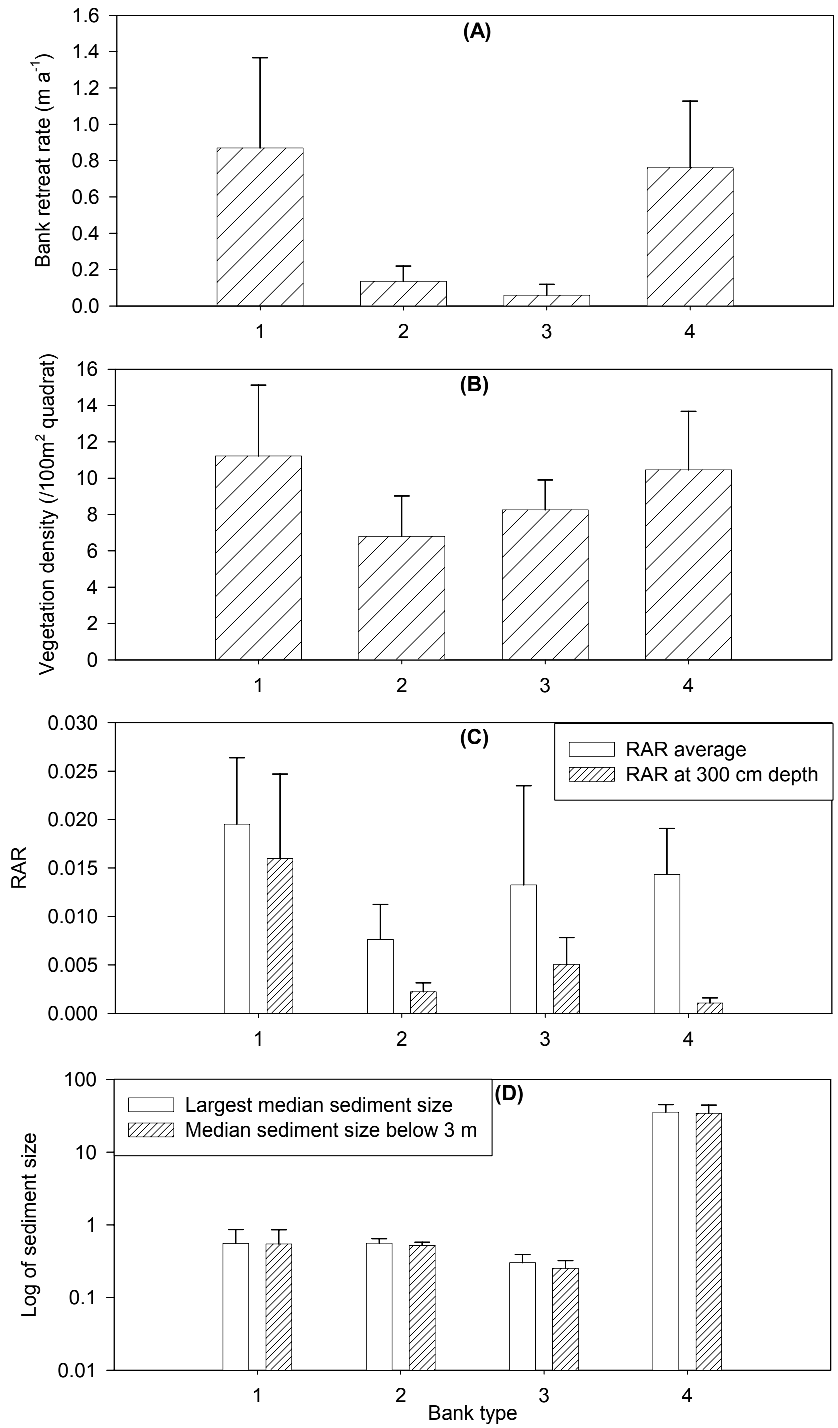


Figure 4.14 – Characteristics of four bank types: (A) bank retreat rates; (B) vegetation density; (C) RAR values; and (D) log of sediment size.

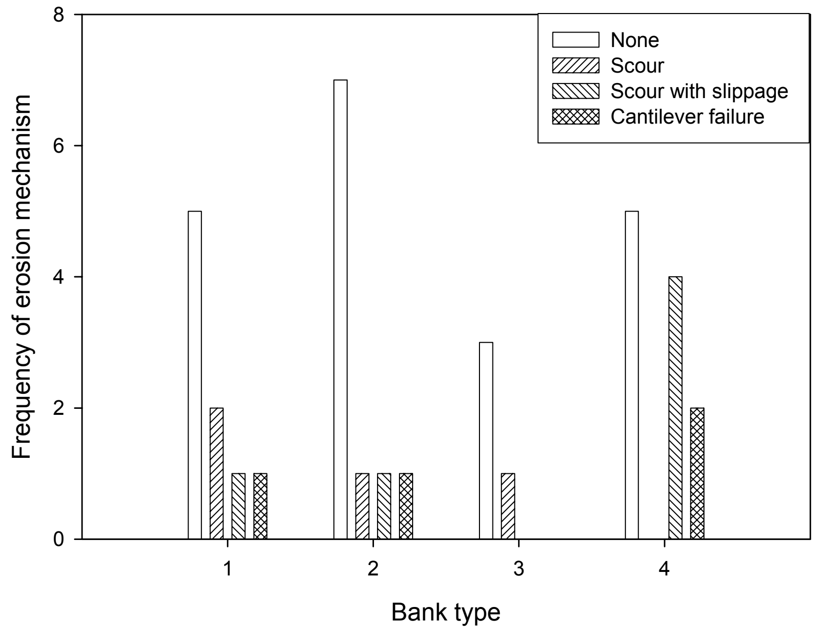


Figure 4.15 – Frequency of types of bank retreat for each stratigraphic bank type.

4.5 Discussion

This study confirms the complex nature of erosion and bank retreat identified in previous studies. While bank angle was identified as the predominant factor that explained variation in bank retreat, the main outcome of this study was that bank retreat was determined by a suite of interconnected factors. Curvature, bank geometry, specific stream power and, to a lesser extent, basal RAR and possibly sediment size all combined to influence retreat rates. These relationships have been shown previously with curvature (Hudson and Kesel 2000), bank geometry (Laubel *et al.* 2003), hydrological characteristics, such as specific stream power and discharge (Nanson and Hickin 1986), stratigraphy (Dapporto *et al.* 2003), and RAR (Abernethy and Rutherfurd 2001). The following discussion focuses on the interaction between these variables and bank retreat rates, the development of the bank models and the importance of parameter thresholds in bank retreat.

4.5.1 Identification and quantification of factors affecting bank retreat

The PCA identified curvature, specific stream power, exposed bank height and bank angle as major correlates with streambank retreat. Bank retreat rates were not affected linearly by any of these factors. Instead, all had thresholds beyond which retreat could occur (bank height: > 3.25 m; bank angle: > 45°; specific stream power: > 130 W m^{-2}; curvature: < 2.0) (Section 4.4.2). Bank retreat rate was very low until these thresholds were exceeded, after which retreat rate became highly variable (from 0 – ~3.0 m a^{-1}). Once these thresholds were passed, variations in bank angle explained the variations in bank retreat – steeper banks (> 45°) were more prone to failure following scour of their base and so were prone to greater bank retreat. These relationships are illustrated in an empirical model (Figure 4.16).

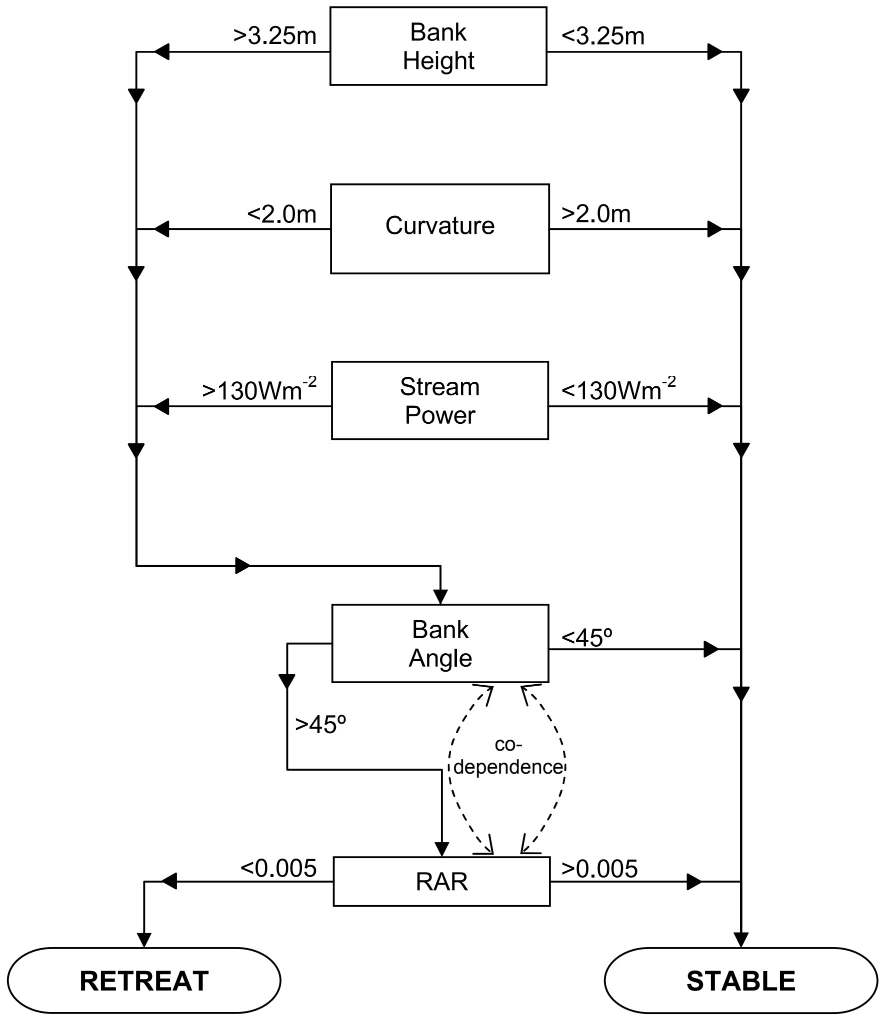


Figure 4.16 – Conceptual model explaining the parameters affecting bank retreat at the study sites in the 2003/2004 wet season and identifying the thresholds that existed for each parameter.

Previous research has illustrated an association between bank angle and bank retreat rates as either sole or joint contributor, in connection with other bank and riparian factors. For example, Ginsberg and Perillo (1990) showed that the angle of banks in the Bahia Blanca estuary in Argentina was the predominant factor predisposing banks to rotational slumping. Rinaldi and Casagli (1999) showed that stability of heterogeneous banks in the Sieve River in Italy was controlled largely by bank angle, with an increase in bank slopes resulting in greater bank retreat. Dapporto *et al.* (2003) also observed decreased bank stability on the Arno River in Italy associated with increased bank angle. However, both Rinaldi and Casagli (1999) and Dapporto *et al.* (2003) stressed the influence of height in controlling stability. In this study, the impact of bank angle and height is more complex, because of the thresholds that need to be crossed before the influence of bank angle is observed.

These thresholds are important in relation to bank stability and resistance to flow. It appears that while the study banks could withstand the shear stresses of direct stream flow and gravitational force under favourable conditions of curvature, bank angle, bank height and stream flow, once the thresholds for these factors had been exceeded, they acted in concert to produce conditions that were favourable for bank retreat. Unless these bank conditions were satisfied, the role of bank angle in preventing or promoting retreat was limited. This is an important issue because many stream managers and land holders regard steep banks as being considerably more at risk of moving, but clearly bank angle played no role in bank retreat rate until the thresholds of the active variables were reached. The factors that are important in a particular stream/river are dependent on regional and local conditions, including climate, hydrology, vegetation and stratigraphy (Hooke 1980, Walker and Rutherfurd 1999). The variables that were active in this study are discussed further below.

Bank geometry

Bank retreat was limited on banks with exposed bank heights lower than 3.25 m, irrespective of bank angle. Banks greater than this height retreated at variable rates, with some being stable and others exhibiting high rates of bank retreat. These variations in retreat rates were explained by bank angle. Banks greater than 3.25 m and with slopes less than 45° retreated slowly, but banks of similar height with slopes steeper than 45° experienced much greater retreat.

Bank height and angle have important implications for stability, as they affect bank weight and the gravitational stresses provided by it and they influence a bank's exposure to the direct stresses provided by fluvial entrainment (Abernethy 1999, Dapporto *et al.* 2003, Ponce 1978, Thorne 1991). All forms of erosion observed in the three study streams were related to direct scour or cantilever failure. They were thus dependent not on the influence of bank height and angle on the stresses exerted by bank material weight, but on the stresses provided directly by the stream flow and by the basal exposure of higher banks to the stream flow due to lack of reinforcement.

The relevance of bank height and angle to fluvial entrainment of bank sediment particles has been discussed far less than has their effects on within-bank stability. However, the influence of bank height and angle on these processes is considerable as they govern the degree of exposure to which the bank is subjected (Section 1.5.7, Rinaldi and Casagli 1999). Higher banks have a greater portion exposed to primary and secondary flows and thus are more likely to retreat as a result of direct scour (Laubel *et al.* 1999, Nanson and Hickin 1986). This is especially the case with regard to composite streambanks where the lower stratum is often composed of easily eroded non-cohesive sediment (Okagbue and Abam 1986). Higher, steeper banks are also less likely to be penetrated by stabilising root networks (Abernethy 1999).

The bank height and angle thresholds observed in this study were thus critical in allowing bank retreat to occur. Banks exceeding these thresholds 1) had greater portions exposed perennially to fluvial processes; 2) had greater portions that were inundated for longer periods during floods; and 3) were less likely to be penetrated by dense root networks leaving them even more exposed to fluvial processes.

<u>Vegetation and roots</u>

Most of the research involving bank angle and height relates to their indirect effect on bank retreat rates through their control of vegetation colonisation (Abernethy 1999, Abernethy and Rutherfurd 1998, Phillips *et al.* 2001). Higher banks with steeper angles are less likely to be colonised by vegetation at their base and are thus more susceptible to the stresses provided by primary and secondary flow velocities. This is especially the case in banks with non-cohesive basal sedimentary units (Nanson and Hickin 1986). The potential for fluvial entrainment of bank particles is reduced by the presence of vegetation and roots through an associated increase in bank resistance (Abernethy and Rutherfurd 1998, Dunaway *et al.* 1994) and hydraulic roughness provided by the vegetation (Abernethy and Rutherfurd 1998, Masterman and Thorne 1992). This contribution of vegetation to bank resistance is irrelevant on steep banks, which are not colonised by vegetation and, thus, root reinforcement is limited to the upper bank (Abernethy and Rutherfurd 1998, Phillips *et al.* 2001). This is especially the case in perennial streams where roots of bank-top vegetation are limited to the upper profile because of the effects of waterlogging (Coutts and Philipson 1978, Stone and Kalisz 1991).

In this study, vegetation variables were shown to have little direct effect upon bank retreat rates. No direct relationship was identified between RAR and bank retreat, regardless of which RAR measure (mean, 1.0 m depth, 3.0 m depth) was used. Above-ground vegetation properties (density, DBH etc) were also found to have little impact upon overall bank retreat. This apparent lack of vegetation contribution to bank retreat has been shown in other studies (e.g.

Nanson and Hickin 1986). However, RARs and bank angle were interrelated. RAR at a depth of 3.0 m was found to have a significant relationship with bank angle. Maximum bank angle followed a significant exponentially decaying relationship with increasing RARs at a depth of 3.0 m, indicating that variability in bank angle reduced markedly as RARs (3.0 m) increased (Figure 4.11). This marked drop in slope variation was obvious at RAR values of about 0.005-0.01. This relationship suggests, firstly, that basal scour was responsible for much of the variation in bank angle and thus streambank retreat that occurred during the study period; and, secondly, that RARs at depths played some role in preventing bank undercutting. This was evident at several sites during the study – JA0006, JA0008 and LI0006 all had vegetation densities of more than 15 individuals in the 10×10 m quadrat and RARs at the bank top in excess of 0.016. However, RARs dropped markedly below 3.0 m. All sites had RARs of less than 0.0094 below 3.0 m and experienced toe or near-toe scour as a result (Section 3.3.2). Regardless of the actual numbers (which may or may not vary in streams of different size), of importance here is that while a bank may be densely vegetated and have dense root networks, the susceptibility to bank retreat is affected little by these characteristics and, unless the vegetation has deep root networks, the bank toe is poorly protected against fluvial entrainment.

The importance of basal roots in reducing fluvial entrainment is three-fold: they contribute directly to strengthening of banks by increasing the soil-root cohesion, they provide organic matter that improves aggregation and stability, and they create backwaters that slow near-bank velocities (Abernethy and Rutherfurd 1999b, Gyssels and Poesen 2003). While the importance of the first point is obvious as more gradually sloped banks are more likely to be colonised by vegetation and their roots are more likely to be dense at the bank-channel interface (Abernethy and Rutherfurd 1998), it is the second point that warrants special mention. Overhanging roots that provide an armouring effect on banks curb bank retreat rates by effectively slowing and diverting both primary and secondary flows away from the bank (see Appendix B.20). These types of root networks were particularly obvious in Liverpool Creek where lower banks enabled the roots to extend to the base of the bank and provide extra cohesion. Additionally, when sediment was removed from the soil-root matrix, exposed woody roots provided an armouring effect that directed flow away from the bank. This phenomenon was not fully investigated in this study. However, it only occurred on low gradually sloped banks and given that no discrepancy existed in bank retreat rates between low, gradually sloped banks with and without armouring roots, the flow diversion created by these roots in these situations can largely be ignored.

Specific stream power

Data on specific stream power for Liverpool Creek and Thornton Creek were calculated using flow characteristics from the 2003/2004 wet season. As Jarra Creek is not gauged, conservative estimates of flow characteristics were calculated using Manning's equation. The Jarra Creek statistics can be used relatively safely given reported estimates of the size of the flood: landholders in the Jarra Creek sub-catchment reported bankfull flows during the 2003/2004 wet season, and flood debris at bankfull height suggested similar flood levels. Liverpool Creek recorded bankfull flows at most sites. Given that both streams are similar in catchment and stream size and share similar source zones – they are located in the same mountain range – bankfull flows and associated specific stream power data could be used with some confidence.

Specific stream power was identified as a contributor to bank retreat rates on the three study streams. The PCA identified a relationship between specific stream power and Axis 2 – the axis explained largely by bank retreat rate. The relationship between specific stream power and bank retreat in this study, however, was not linear, largely due to the effects of other variables. As discussed above, those sites with greater specific stream power were more variable in the rates that they moved, due to variations in bank angle. Once the identified threshold of about 130 W m^{-2} was exceeded there was enough power to perform geomorphic work on the steeper banks. Thus, in the three study streams, the influence of specific stream power on bank retreat was negligible unless thresholds of curvature, bank angle and bank height were also exceeded. This masking effect of other variables was not unexpected given that the range in specific stream power at the present study sites was relatively small. Examination of sites over a larger geographic range, experiencing longer lasting flows and including steeper reaches may produce greater ranges in specific stream power and show some effect. Nevertheless, a relationship is present in this study between specific stream power and retreat rates, in conjunction with other variables.

Previous research has identified relationships between various measures of stream power and bank retreat. Abernethy and Rutherfurd (1998), for example, showed that variations in specific stream power provide a good estimate of flow erosivity and, thus, likelihood of streambank retreat. Similarly, Laubel *et al.* (2003) showed that specific stream power contributed significantly to bank retreat of the lower bank – explained, firstly, by the continual exposure of the bank toe to fluvial entrainment and, secondly, by the greater velocities and shear stresses it is exposed to, even at bankfull stage. Considering the scour-related erosional processes active in this study, similar conclusions with regards to the duration of exposure of the bank toe to fluvial entrainment can be made here. Despite similarities between this study and others, no research was found that identified this complex relationship between specific stream power thresholds, other active variables and bank retreat.

Curvature

It is evident that bank retreat will be most significant on bends with certain curvature (r_m/W_m) values. In this study, maximum bank retreat rates occurred at a curvature of 1.0-1.5, with a progressive decline in retreat rates associated with increases in curvature above 1.5 (Figure 4.8). In the study streams there were small reaches, especially on Jarra Creek, that took the form of compound symmetrical and asymmetrical meanders, but most bends within the study reaches were identified as simple meanders that were either symmetrical or asymmetrical (Brice 1974). These characteristics largely result from the short floodplains that these streams flow through and the influence that the complex heterogeneity of much of the floodplain has on bank retreat.

Similar results have been found in other catchments with heterogeneous banks. For example, Hudson and Kesel (2000) showed that the bank retreat rates of meander bends on the lower Mississippi, which flows through complex heterogeneous floodplain deposits, peaked at a curvature of about 1.0 and declined steadily with increased curvature values. Likewise, Hooke (1987) determined that maximum bank retreat rates on the River Dane in the United Kingdom occurred at curvature values of 1.0-2.0, with a similarly gradual decline in retreat rates associated with increased curvature. It is interesting to note that the results of this study and Hooke (1987) are analogous with the Mississippi study of Hudson and Kesel (2000), despite the contrast in scale between the Mississippi and the much smaller River Dane and tropical Queensland systems. Hudson and Kesel (2000) argued that their results compared with Hooke (1987) largely due to the influence of stratigraphic complexity, with rates of bank retreat controlled by sedimentary units of varying cohesion and resistance – from resistant clay plugs to sand and gravel lenses. The indirect relationship identified between stratigraphy, bank types and bank retreat suggest similar indirect control of sediment on curvature – most sites that moved at greater rates had both low curvature and a lower non-cohesive sedimentary unit.

It also appears that heterogeneous banks provide limitations to typical downstream translation of the retreat meander bends, instead dictating which direction the meander bends retreat according to which banks are more resistant to fluvial entrainment (Knighton 1998). This provides difficulties in management of bank retreat across floodplains as direction and rate of retreat are difficult to predict without knowledge of the complex interaction between stratigraphy, curvature and retreat.

4.5.2 Bank models, sediment, stratigraphy and their effect on bank retreat and angle

Generally, stable steep banks can be maintained when they are composed of homogeneous cohesive deposits, as they can resist fluvial stresses and restrict bank retreat rates. However, in heterogeneous banks, which are often composed of one or more non-cohesive sedimentary units, steep banks are often created via direct fluvial scour of the non-cohesive unit (Gilvear *et al.* 2000). Dapporto *et al.* (2003) noted the predominance of cantilever-style failures on composite banks resulting from bank over-steepening and overhangs. Similarly, Okagbue and Abam (1986) reasoned that failure of upper cohesive strata of banks in the Niger Delta were triggered by bank steepening and overhangs as a consequence of scour of the basal non-cohesive stratum, while Gilvear *et al.* (2000) inferred that streambank retreat primarily from cantilever failure following bank steepening was due to undermining of less resistant basal strata.

No relationship was identified between stratigraphy and bank angle, RAR or actual bank retreat in this study. This is an interesting finding given the extensive research that has identified sediment and stratigraphy as predominant bank retreat instigators because of its role in determining bank resistance to flow (e.g. Dapporto *et al.* 2003, Okagbue and Abam 1986, Thorne and Tovey 1981). However, field observations provide some evidence that several of the sites that retreated quickly were influenced to some extent by their lower sandy-gravel stratum. For instance, both JA0003 and JA0010 had lower strata consisting of unconsolidated coarse grain sizes at the angle of repose (Table 4.1). These sedimentary units were mostly old bed or point bar material subsequently overlain by silty-sand deposits (Collinson 1996). Both experienced bank retreat through scour-induced failure or slippage mechanisms (erosion mechanism i) (> 3.0 m in the case of JA0003 and > 1.0 m in the case of JA0010). This bottom stratum was easily eroded due to the low flow resistance provided by its lack of cohesion. While failed bank portions accumulating at the bank toe may provide some resistance against the flow (Darby *et al.* 2002, Okagbue and Abam 1986), this resistance is only temporary – once these failed portions are transported downstream or further down the bank, the lower sedimentary units are again exposed to the shear stresses of the stream flow.

The statistical analyses could not confirm these relationships because of the limited sample size and the large suite of factors that have been shown to trigger bank retreat. However, even in studies with larger sample sizes, identification of absolute relationships between sediment size, stratigraphy and bank retreat is problematic. This is largely due to the complex stratigraphic interactions between the bank sedimentary units (Huang and Nanson 1998).

Classifying banks according to their stratigraphy is a simple method of analysing different stratigraphic influences on bank retreat. The four bank types identified in this study (2 homogeneous and 2 heterogeneous) seemed to be unrelated either to other bank features or to bank retreat, contrasting with the findings of Dapporto *et al.* (2003). While there was some link between RAR and bank type, with Bank Type 4 having very low RARs below 3.0 m regardless of vegetation density, only minor inter-bank type differences were observed with regard to other characteristics, especially bank angle and bank retreat. This suggests that, with the exception of its relationship with RAR, overall stratigraphy plays little part in either controlling bank retreat rates directly or affecting the other influences on bank retreat rate.

Interestingly, however, the two heterogeneous banks, both of which included a similar coarser stratum, were not similar in other characteristics. Heterogeneous and homogeneous banks usually behave differently (Dapporto *et al.* 2003, Hudson and Kesel 2000, Rinaldi and Casagli 1999), but in this study, banks of Type 4 (heterogeneous) were more similar to banks of the homogeneous Bank Type 1 than those of the heterogeneous Bank Type 3. Banks of Type 4 underwent significantly greater bank retreat rates than those of Type 3, due to a combination of factors, including differences in bank angle and RAR below 3.0 m depth and the existence of the basal sandy-gravel stratum. However, while banks of Type 1 were similar in average height and rates of bank retreat to banks of Type 4, they were generally more gradually sloped. So, regardless of bank retreat occurring, it appears that banks of Type 1 are generally more able to maintain higher, gradual slopes due to finer, more resistant bank material, while banks of Type 4 cannot maintain these gradual slopes because of their coarse-grained basal sedimentary unit.

4.5.3 Thresholds, magnitude and frequency

This study demonstrates the importance of thresholds in fluvial geomorphology. Their relevance in geomorphic studies has been discussed widely, especially in relation to magnitude and frequency of forces acting on channel boundaries. Wolman and Miller (1960) introduced the notion that only events of particular magnitude and frequency enable the thresholds of geomorphic mechanisms to be exceeded and for work to be performed. There is extensive debate over the influence of flood magnitude and frequency on the amount of geomorphic work that a flood performs: is more landscape-modifying work accomplished by moderately frequent, lower magnitude events or by the low frequency, high magnitude events (Wolman and Miller 1960, Baker 1977, Erskine 1996)?

In this study, the relative magnitude and frequency of the studied event is unknown, as there was no opportunity to make direct comparisons with previous events. However, the local variable thresholds that were exceeded during the 2003/2004 event are of importance, as the size of a flood is irrelevant unless the site geomorphic thresholds are known. While the 2003/2004 event was of relatively low magnitude and relatively high frequency (AEP = 2.27 in Liverpool Creek), it still caused thresholds in specific stream power, bank height and angle, and curvature to be exceeded at some sites, enabling work to be performed and bank retreat to occur. Baker (1977), Brewer and Lewin (1998) and Kochel (1988) have similarly discussed the importance of other variables in combination with magnitude and frequency of events in performing geomorphic work. Assuming that the effect of floods is largely based on the time that they exceed the thresholds, greater retreat than that seen in the 2003/2004 wet season could be commonly expected with larger and longer-lasting flows, such as those experienced during cyclonic events.

The potential effects of less frequent, higher magnitude events on bank retreat rates are arguable, but may not differ considerably from the 2003/2004 wet season because in Liverpool Creek and Jarra Creek, bankfull level was attained. These wet tropical streams, like many others in the north-eastern Queensland region, experience regular large events. Channels are 'adapted' to these conditions in that their size is restricted and flow is frequently forced out of the channel (overtopping of banks), such that specific stream power and potential for work are limited, regardless of the magnitude or duration of a flow (Kapitzke *et al.* 1996). However, it is probable that at sites where curvature, specific stream power, bank height and bank angle thresholds are exceeded, even low magnitude, frequently occurring events, especially in Jarra Creek, can result in geomorphic work.

4.6 Conclusions and management implications

This study shows the complex nature of the relationship between streambank retreat and potential local-scale variables. It suggests a synergistic relationship among variables that controls bank retreat (Figure 4.16). Bank angle, specific stream power, bank height and curvature together explain variation in bank retreat and bank angle explains variation amongst the other variables. Similarly, RAR explains bank retreat variation amongst bank angles, which in turn act to influence RAR at depths – steep bank angles do not promote root growth at great depths down the bank profile. Furthermore, bank stratigraphy was shown to play some role in determining bank angle.

This complexity causes difficulty in management, because of the lack of a single major control of bank retreat. The large variability of bank retreat, once variable thresholds have been exceeded, means a definitive answer over whether a bank will retreat cannot be determined. However, while specific stream power and curvature are difficult to control in 'natural' streams, a balance needs to be established between bank height, angle and basal root densities to ensure that these thresholds are not exceeded, so that root growth is encouraged, increasing resistance of the bank to primary and secondary flow and reduce the impact of curvature.

CHAPTER 5
ROOTS AND EROSION OF THE BANK FACE

5.1 Introduction

It was established in the previous chapter that as root density at the bank toe of the study sites increased, the banks became less steep and retreated at a slower rate. Temperate studies have shown that roots contribute to erosion control by increasing cohesion, by improving sediment aggregation through the release of binding agents and by diverting primary and secondary flows by exposed root systems (Abernethy 1999, Gyssels and Poesen 2003, Thorne 1990). However, in determining whether a bank is likely to retreat, the variability of RAR down the bank face is likely to be just as important as RAR at the mean or at particular depths, because it might cause different amounts of erosion at different depths which may ultimately make other points on the bank more vulnerable to erosion. Undercutting, for example, will eventually result in cantilever failure of the bank top. Variations in root densities, due to changes in local factors such as depth or stratigraphy, can thus play an important role in controlling overall bank retreat (e.g. Abernethy 1999).

It is therefore important to identify patterns of RAR with depth, sediment type and other local characteristics before investigating the contribution of roots to the stability and resistance of banks to fluvial entrainment as these variations can influence erosion susceptibility of a bank. Therefore, this chapter investigates the following questions:

- are there significant differences in RAR between streams;
- are there significant relationships between RAR and above-ground vegetation characteristics;
- are there significant differences in RAR with depth or sediment type; and
- are there significant relationships between RAR and other local variables and erosion at intervals up the study banks?

5.2 Methods

The methods used to address the chapter aims are summarised in Figure 5.1, and described further in subsequent sections.

1. WHAT ARE THE RELATIONSHIPS BETWEEN RAR & ABOVE-GROUND VEGETATION CHARACTERISTICS?

↓

Approach:
- Field – RAR measured at 1.0, 2.0 & 3.0 m depths; vegetation characteristics measured for each site (DBH, tree density, tree height, riparian width)
- Statistics – Regressions of vegetation characteristics & each of the 3 RAR readings

2. WHAT ARE THE RELATIONSHIPS BETWEEN RAR & SEDIMENT?

↓

Approach:
- Field – RAR measurements and sediment components (sand, gravel, clay) recorded at 0.5 m intervals
- Statistics – Regressions of RAR against each sediment constituent

3. WHAT ARE THE RELATIONSHIPS BETWEEN RAR & DEPTH?

↓

Approach:
- Field – Depths of RAR measurements recorded
- Statistics – Depth-averaged RARs for all vegetated sites plotted to illustrate the point of decline in RAR; *t*-tests on the entire data set between RARs above & below 2.0, 2.5 & 3.5 m to identify the point of decline in RAR

4. ARE THERE DIFFERENCES IN RAR BETWEEN STREAMS?

↓

Approach:
- Data from each stream separated into RARs above & below demarcation where RAR clearly declined
- ANOVAs on both sets of RARs to determine differences in RAR between climatological regions & streams

5. ARE THERE RELATIONSHIPS BETWEEN RAR & OTHER LOCAL VARIABLES & EROSION OF THE BANK FACE?

↓

Approach:
- PCAs on wet & wet-dry tropics datasets to investigate the combined influence of depth, height above bank toe, RAR, erosion rate & clay, sand & gravel sediment content
- Regressions to investigate the relationship between erosion & important characteristics identified in the PCAs
- If apparent relationship with only maximum values of variables, regression of maximum values against erosion
- If no obvious relationship in scatter plots, *t*-tests conducted between high & low-value groups of each variable

Figure 5.1 – Summary of the approach taken to address the aims of Chapter 5.

5.2.1 Field methodology

Erosion types and rates were determined using the repeated cross-profiling methodology outlined in Section 3.2.2, and RAR was measured using the profile wall methodology at the bank-channel interface, as described in Section 4.2.4. Additionally, at each study site RAR values were measured at standard depths of 1.0, 2.0 and 3.0 m and at approximately 0.5 m intervals to correspond with the erosion records measured at the same intervals. At some sites, RAR data at exactly 0.5 m intervals were impossible to measure, due to the presence of external roots and difficult bank geometry, so profiles were measured as close to 0.5 m intervals as possible. Bank stratigraphy and geometry were recorded at each point where RAR was mapped, following methods outlined in Sections 4.2.1 and 4.2.2. The same 34 study sites are used in this chapter, allowing a total of 81 RAR readings from vegetated and unvegetated banks in the wet tropics and 78 from the wet-dry tropics. Vegetation characteristics recorded in Section 4.2.3 (density, DBH, riparian width, tree height) are also used in this chapter.

5.2.2 Statistical analysis

Statistical methods in this chapter were largely exploratory so the selection of operations was mostly dependent on the preceding results (Figure 5.1). Therefore, this section briefly describes the statistical methodology, with a more detailed description included with the results.

<u>Root area ratio and above-ground vegetation characteristics relationships</u>

Initial investigations between RAR and other community vegetation characteristics were undertaken to identify any relationship between above- and below-ground morphology and to test the RAR predictive capability of above-ground vegetation characteristics. Above-ground vegetative characteristics were regressed against RAR at different depths (1.0 m, 2.0 m and 3.0 m) to determine the existence of any depth-related relationships between above- and below-ground characteristics. The regression model applied to each relationship was the simplest model that had an appropriate fit.

<u>Root area ratio, depth and sediment type relationships</u>

To determine sediment-RAR relationships, gravel and clay content were plotted against RAR for vegetated sites. This identified simple relationships between sediment and RAR. Actual component percentages were used rather than the grain-size distribution as they allowed relationships between RAR and the finest and coarsest fractions of the sedimentary units to be determined, and indicated more directly which aspects of a sedimentary unit affected root growth. Investigations of the influence of depth on RAR were also undertaken for vegetated sites, as it was likely that RAR would decline at depths of 2.0-3.0 m (Rutherfurd *et al.* 2000). Thus, depth-averaged RARs for all sites and for sites in each region were plotted to illustrate where RARs declined. Subsequently, *t*-tests were conducted on the entire data set to determine whether any significant differences existed between RARs above and below 2.0 m, 2.5 m and 3.0 m. This enabled RAR differences between the upper and lower bank to be identified and tested the theory of RAR decline for temperate systems, outlined above.

Root area ratio and stream/region relationships

Once a depth demarcation point had been established where RAR statistically declined, data from each stream were separated into RARs above and below this demarcation. To determine whether differences existed in RAR between the climatological regions and streams, ANOVAs were performed on each data set to identify where differences in RAR existed.

Erosion and controlling factors

Because of the contrasting climate and hydrology of the wet and wet-dry tropics data (Sections 2.1 and 2.2), separate PCAs were performed for study sites in each region, to investigate the combined influence of depth, height above bank toe, RAR, erosion rate and clay, sand and gravel sediment content. The inclusion of hydrological variables in this analysis was unwarranted as the data were already separated according to hydrological regime and because hydrology was similar between sites within each region. Scatter plots were created to investigate the relationship between erosion and important characteristics identified in the PCAs, and regressions were performed between each variable and erosion to quantify this relationship. The regression model was selected according to the relationship that best fit the data. If there was no direct relationship, but one existed between maximum values of the independent variable and erosion rates, maximum-value groups similar to those set up in Section 4.4.2 were established to illustrate the relationship more clearly. If no obvious relationship could be identified in the scatter plots, *t*-tests were conducted between high and low-value groups of each variable.

5.3 Results

Figure 5.2 is a summary of the results for each chapter aim.

5.3.1 Root area ratios

RAR of all vegetated sites varied within and between sites, ranging between 0.00 and 0.12 ($\bar{x}$ of all RAR readings = 0.02, SE = 0.003). Wet tropics data were similarly variable ($\bar{x}$ = 0.03, SE = 0.004), while variability of Thornton Creek data was lower, with RARs varying between 0.00 and 0.009 ($\bar{x}$ = 0.005, SE = 0.0006). Figures 5.3 to 5.5 show the RAR depth profiles for each site. There was high variability of RAR in the upper 3.0 m of Jarra Creek and Liverpool Creek sites ($\bar{x}$ = 0.039, SE = 0.005, CV = 71%), consistently low but variable RARs below 3.0 m at the same sites ($\bar{x}$ = 0.006, SE = 0.003, CV = 159%) and a general decline in RAR with depth in Thornton Creek sites.

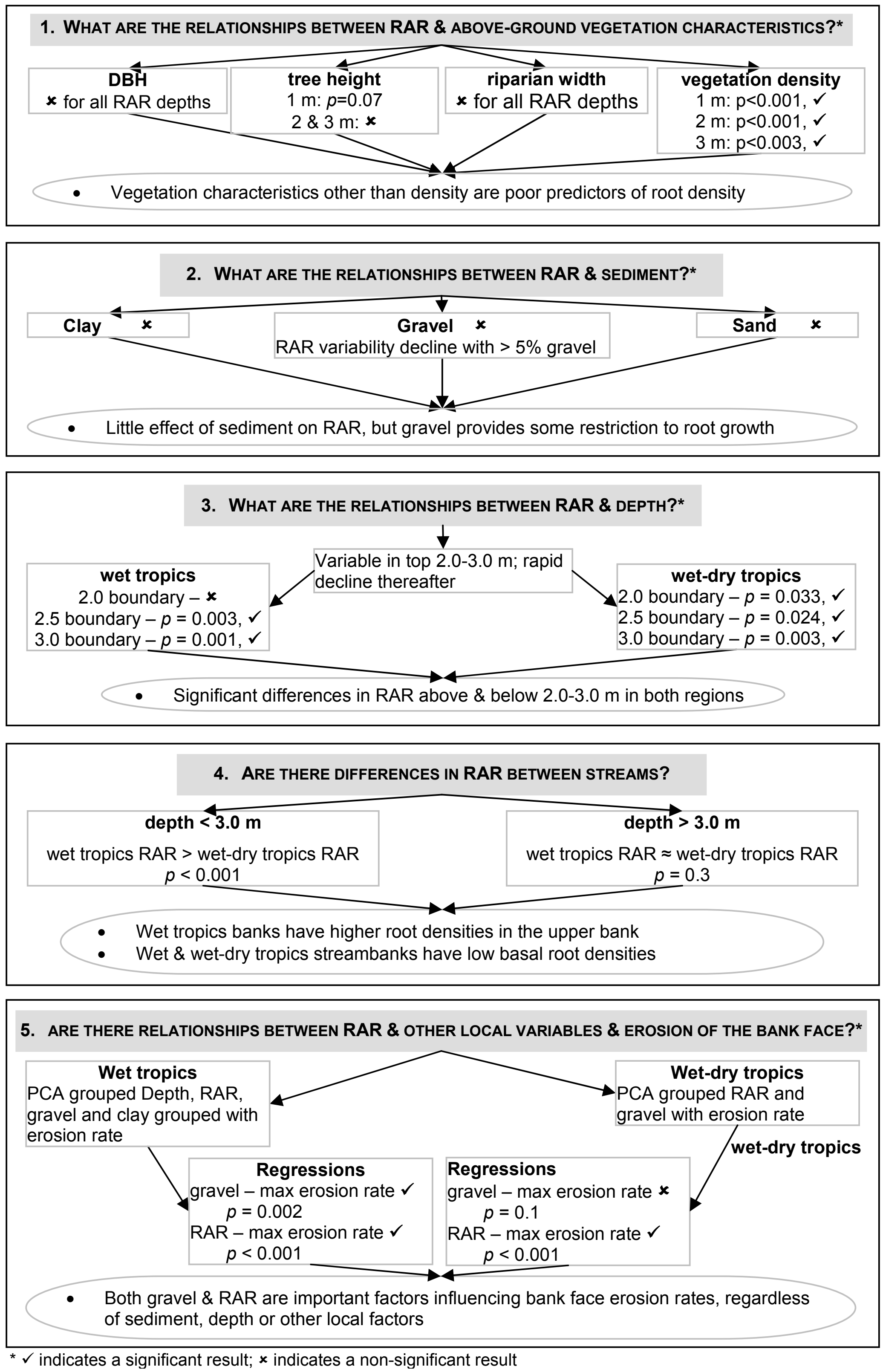


Figure 5.2 – Flowchart summarising the results relevant to each chapter aim.

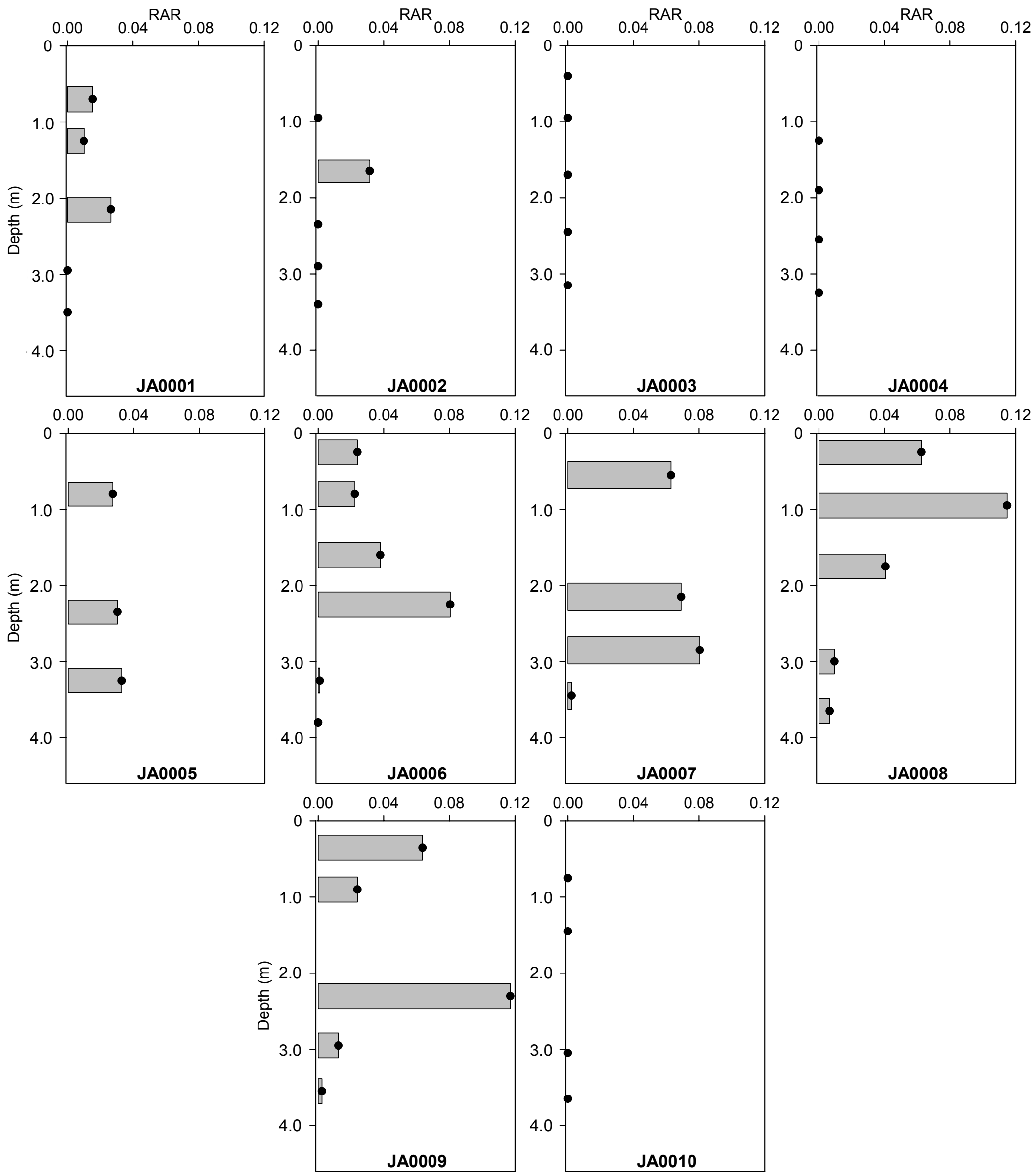


Figure 5.3 – RAR vs. depth profiles for Jarra Creek sites (JA0001 – JA0010), showing the variability of RAR above 3.0 m and the low RARs below 3.0 m depth.

Gaps in RAR data are due to obstructions (trees, exposed roots) or inaccessible bank geometry. Points show the location of RAR measurements down the bank profile.

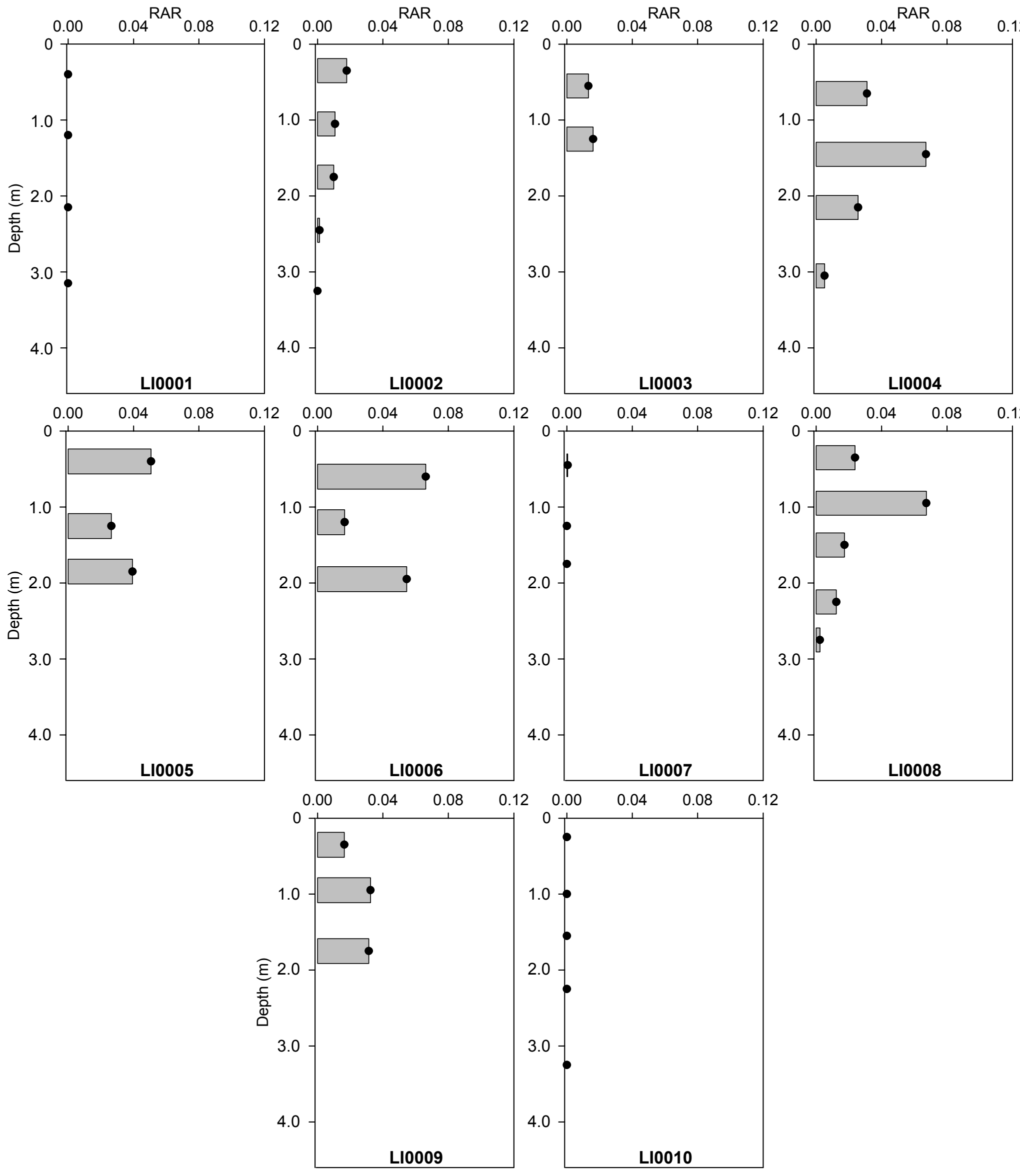


Figure 5.4 – RAR vs. depth profiles for Liverpool Creek sites (LI0001 – LI0010), showing the variability of RAR above 3.0 m and the low RARs below 3.0 m depth.

Points show the location of RAR measurements down the bank.

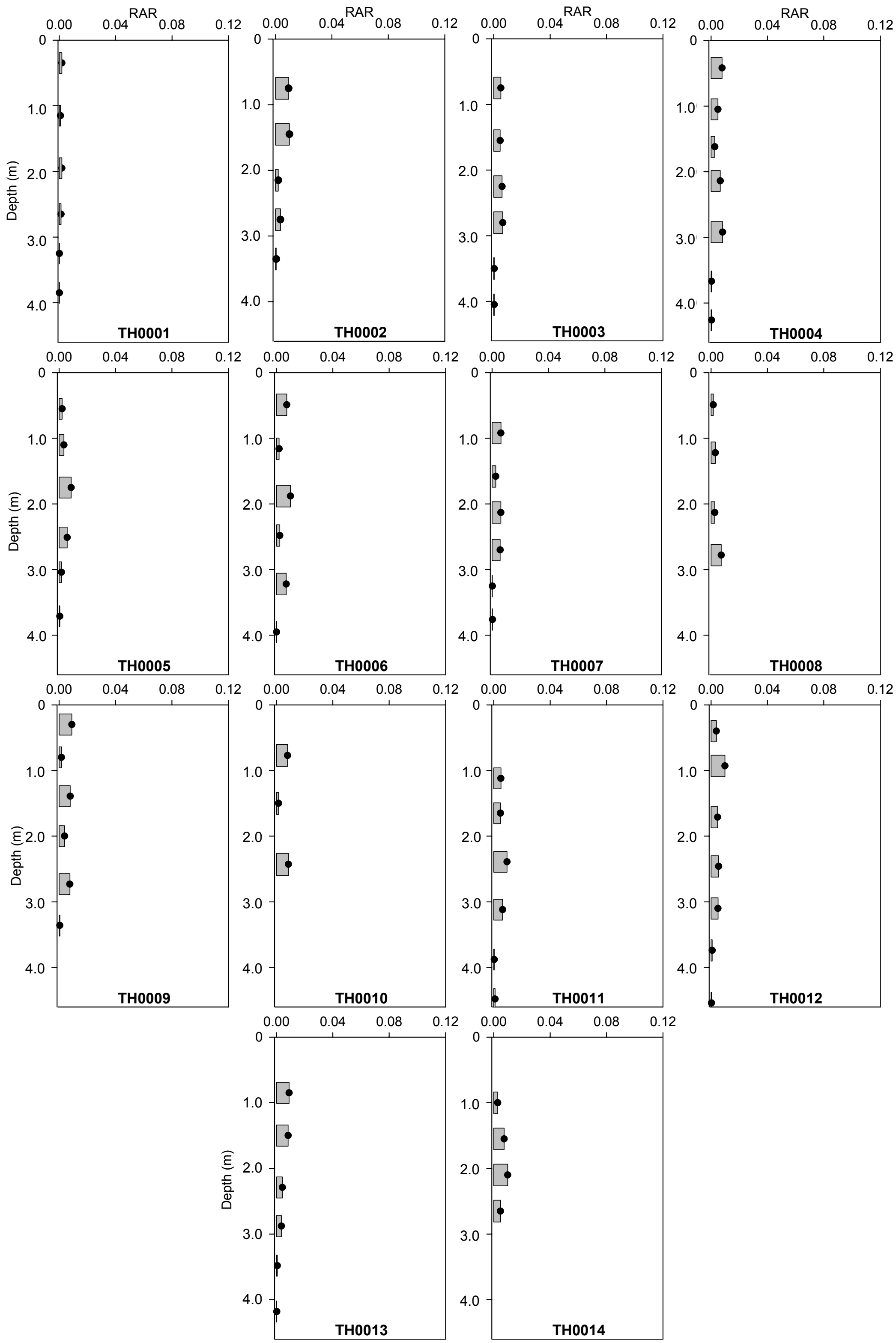


Figure 5.5 – RAR vs. depth profiles for Thornton Creek sites (TH0001 – TH0014), showing the general decline in RAR with depth.

Points show the location of RAR measurements down the bank.

5.3.2 RAR and above-ground vegetation characteristics

No statistically significant relationship (linear or non-linear) existed between RAR and DBH ($r^2 < 0.05$ for all depths, $p > 0.05$) or riparian vegetation width ($r^2 = 0.17$ at 1.0 m depth; $r^2 < 0.03$ at 2.0 m and 3.0 m, $p > 0.05$) at any depth. The strength of the relationship between vegetation height and RAR declined with depth. A non-linear sigmoidal relationship was evident between height and maximum RAR ($r^2 = 0.64$, $p = 0.07$) at 1.0 m depth, while no significant relationship was evident at depths of 2.0 m ($r^2 = 0.02$, $p = 0.4$) or 3.0 m ($r^2 < 0.01$, $p = 0.4$). In the relationship between tree height and maximum RAR, maximum RAR was measured for every 5 m tree height interval to remove any bias in the selection of maximum RARs. The regression was then run between these maximum RARs and their respective tree heights to test whether tree height was a predictor of RAR (Figure 5.6). These groupings, indicated by the inward-facing tick marks, and the relationship between maximum RAR at 1.0 m depth and tree height, follow the model below:

$$y = \frac{0.07}{\left(1 + e^{-\left(\frac{x - x_0}{1.52}\right)}\right)}.$$

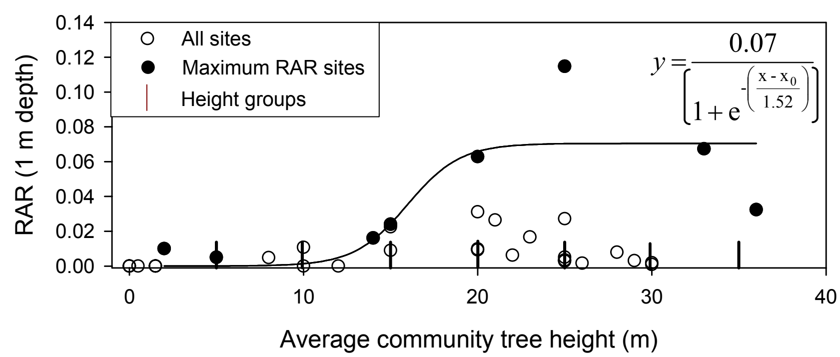


Figure 5.6 – Relationship between mean tree height and RAR at 1.0 m depth, showing the non-linear relationship (r^2 = 0.64, p = 0.07) between height and maximum RAR for each height group following the sigmoidal model shown in the graph.
Height groups are demarcated by inward-facing ticks.

RAR increased linearly with vegetation density at depths of 1.0 m ($r^2 = 0.42$, $p < 0.001$; Figure 5.7) and 2.0 m ($r^2 = 0.39$, $p < 0.001$; Figure 5.8). This relationship weakens at a depth of 3.0 m ($r^2 = 0.26$, $p = 0.003$; Figure 5.9), showing that while community density can provide an indication of community RAR at shallow depths, this predictability declines markedly below 3.0 m.

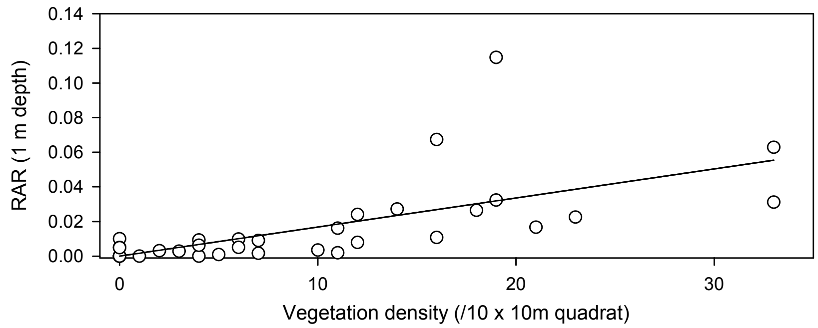


Figure 5.7 – Relationship between community tree density and RAR at 1.0 m depth, showing moderate predictability of RAR at this depth with vegetation density.
Regression results: y = 0.002x + 4.5×10^{-6}; r^2 = 0.42; p < 0.001.

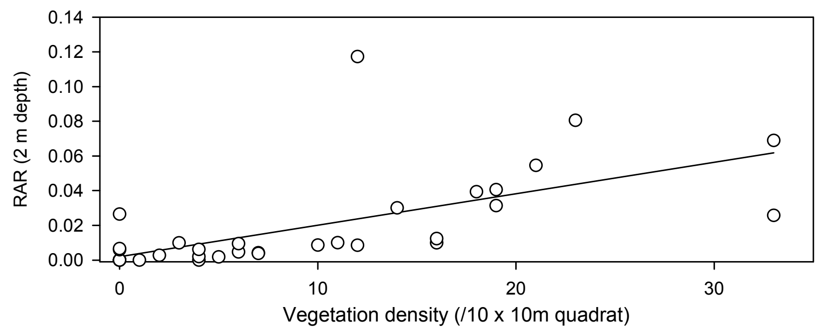


Figure 5.8 – Linear relationship between community tree density and RAR at 2.0 m depth, showing moderate predictability of RAR at this depth with vegetation density.
Regression results: y = 0.002x + 0.002; r^2 = 0.39; p < 0.001.

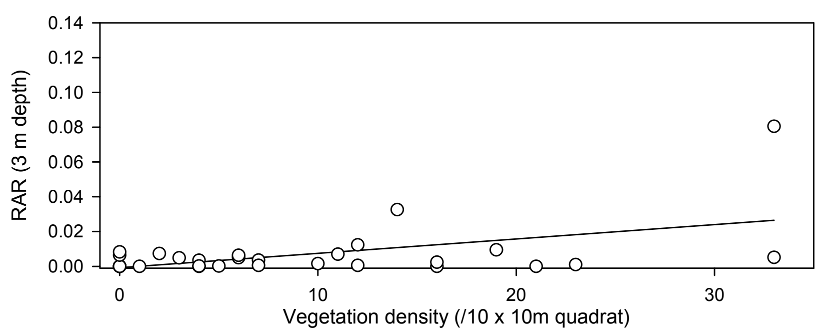


Figure 5.9 – Linear relationship between community tree density and RAR at 3.0 m depth, showing poorer predictability of RAR at this depth with vegetation density.
Regression results: y = 0.0008x - 0.0008; r^2 = 0.26; p = 0.003.

5.3.3 Roots and sediment texture

No significant relationship was detected between clay or gravel content and RAR. Nevertheless, variability in RAR in the wet tropics banks dropped markedly as gravel content increased over 5% (Figure 5.10).

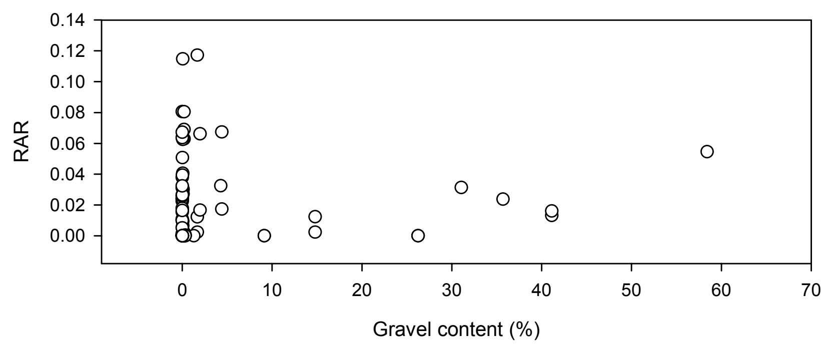


Figure 5.10 – Relationship between gravel content of bank strata and their respective RARs, showing the decline in RAR variability in sediment with > 5% gravel.

5.3.4 Roots and depth

Depth-averaged RAR for all vegetated sites generally declined with depth (0.031 at 0-0.5 m depth to < 0.001 at > 4.0 m depth) (Figure 5.11), although this decline was more apparent at depths between 2.5 m and 3.0 m. Variation about the mean for each depth group was considerable (CV up to 120%), partly due to the inclusion of both wet tropical and wet-dry tropical data – both Jarra Creek and Liverpool Creek had much denser and more variable root networks than Thornton Creek. However, separate plots of Jarra Creek and Liverpool Creek (wet tropics) data and Thornton Creek (wet-dry tropics) data show similar trends of RAR with depth and similar demarcations between RARs above and below 2.5-3.0 m (Figure 5.12 and Figure 5.13). Mean wet tropics RARs dropped from 0.037 at 0-0.5 m depth to 0.01 at 3.5-4.0 m depth, while wet-dry tropics RARs dropped from 0.008 at 0-0.5 m depth to < 0.001 at > 4.0 m depth. Variation in depth-averaged RAR values was less for the Thornton Creek data (CV up to 74%) than the wet tropical data (CV up to 82%).

Separate *t*-tests between RAR above and below the 2.0, 2.5 and 3.0 m demarcation depths were carried out to determine where significant differences lay. Figure 5.14 illustrates the results of the *t*-tests conducted on the entire vegetated data set and shows that RAR was significantly higher in the top 2.5 m ($p = 0.002$) or 3.0 m ($p = 0.001$) than lower down in the bank. The *t*-test for RAR above and below 2.0 m depths produced non-significant results ($p = 0.071$).

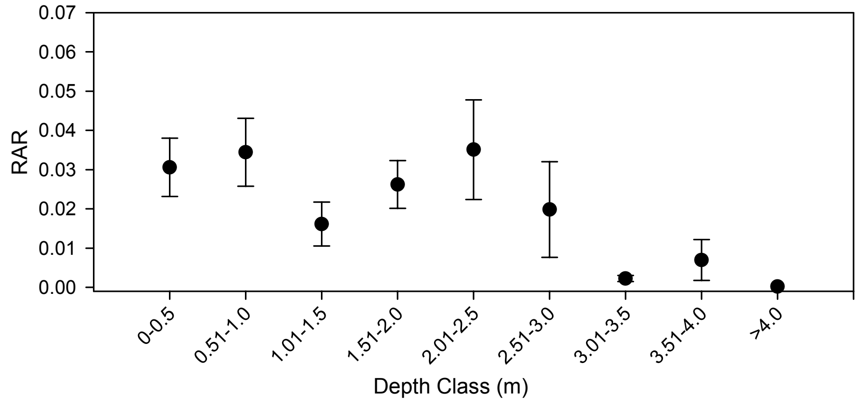


Figure 5.11 – Relationship between RAR ($\bar{x}$ ± SE) and depth at all vegetated study sites (both wet and wet-dry tropics data).

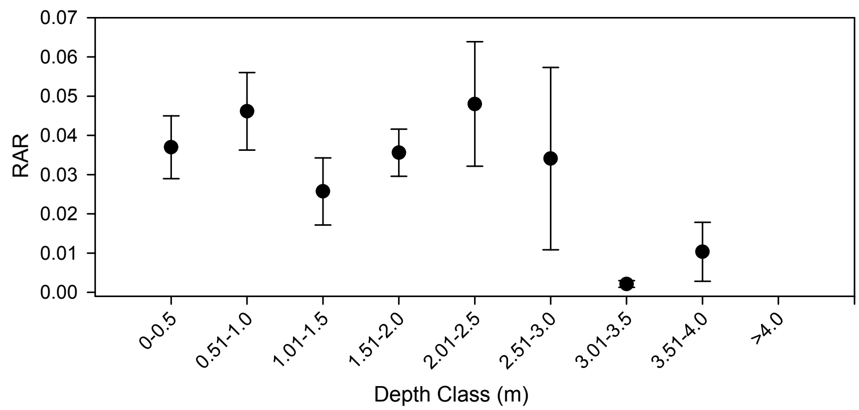


Figure 5.12 – Relationship between RAR ($\bar{x}$ ± SE) and depth for vegetated wet tropics study sites.

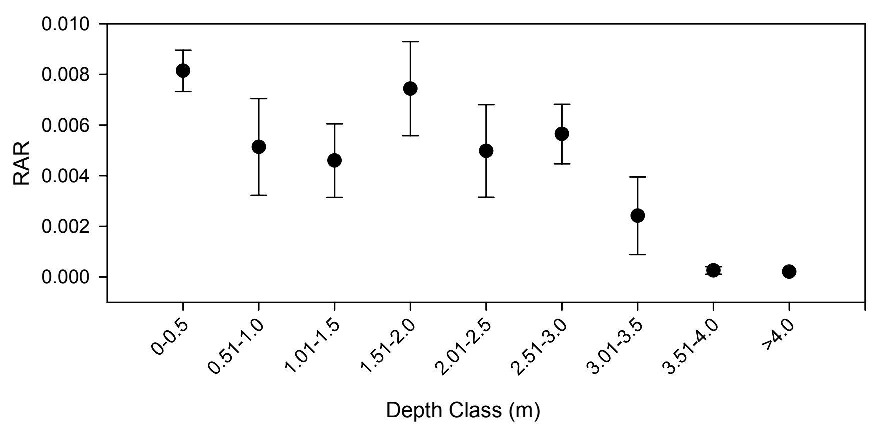


Figure 5.13 – Relationship between RAR ($\bar{x}$ ± SE) and depth for vegetated wet-dry tropics study sites.

Note the difference in scale of the y-axis from the previous two figures.

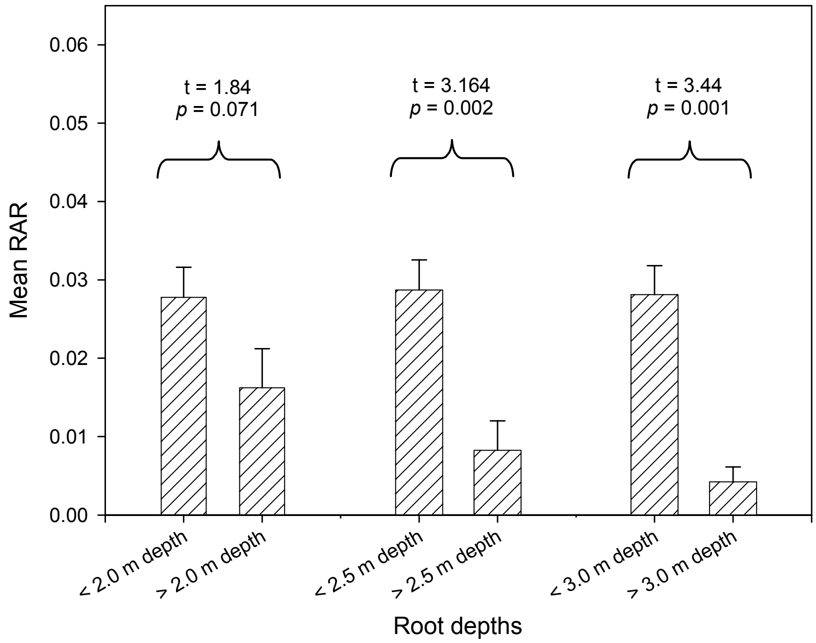


Figure 5.14 – RAR ($\bar{x}$ ± SE) of all vegetated sites above and below indicated depth demarcations.

Results of *t*-tests between RARs of the different depth groups are shown.

Separate wet tropics data showed that RARs were again significantly different above and below the 2.5 m ($p = 0.003$) and 3.0 m ($p = 0.001$) boundaries (Figure 5.15). No significant difference existed above and below the 2.0 m boundary ($p = 0.21$), largely due to the high variance in RARs around the 2.0-2.5 m mark. Differences in RAR were more noticeable in Thornton Creek. The wet-dry tropical RARs were all significantly greater above than below the three depth demarcations (2.0 m – $p = 0.033$; 2.5 m – $p = 0.024$; 3.0 m – $p = 0.003$) (Figure 5.16). All of these results indicate that RAR, and thus root penetration and occurrence, is significantly lower beyond depths of 2.0-3.0 m.

5.3.5 RAR differences between streams

ANOVAs were used to investigate differences between streams in RAR at depths less than and greater than 3.0 m. The ANOVAs showed that RARs were significantly higher in wet tropical than in the wet-dry tropical sites at depths shallower than 3.0 m ($F_{2,119} = 13.86$, $p < 0.001$). *Post hoc* Tukey's tests showed that these differences lay between Thornton Creek and both Jarra Creek and Liverpool Creek (JA-TH: $p < 0.001$; LI-TH: $p = 0.007$; Figure 5.17). However, these differences in RARs were not observed at depths greater than 3.0 m ($F_{2,36} = 1.23$, $p = 0.3$).

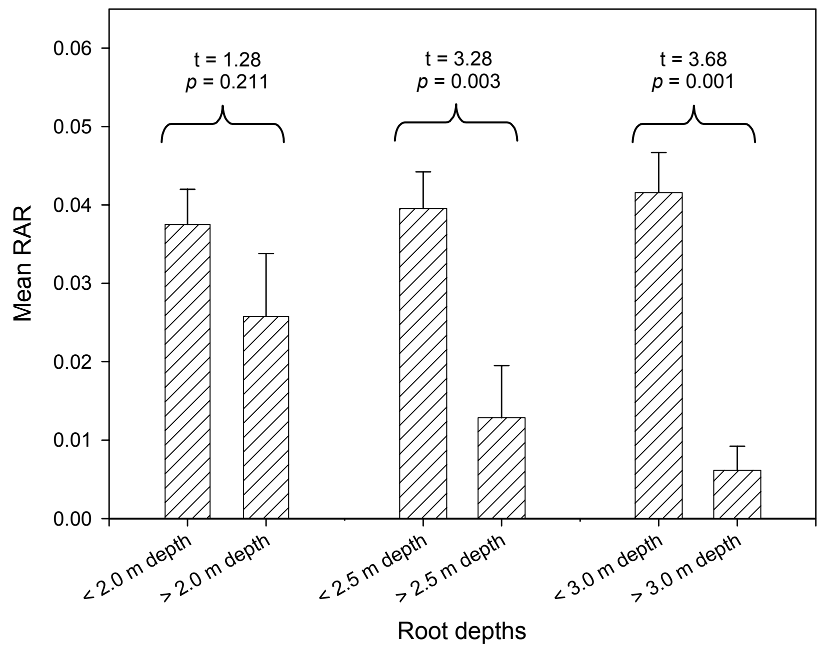


Figure 5.15 – RAR ($\bar{x}$ ± SE) of vegetated wet tropics sites above and below indicated depth demarcations.

Results of *t*-tests between RARs of the different depth groups are shown.

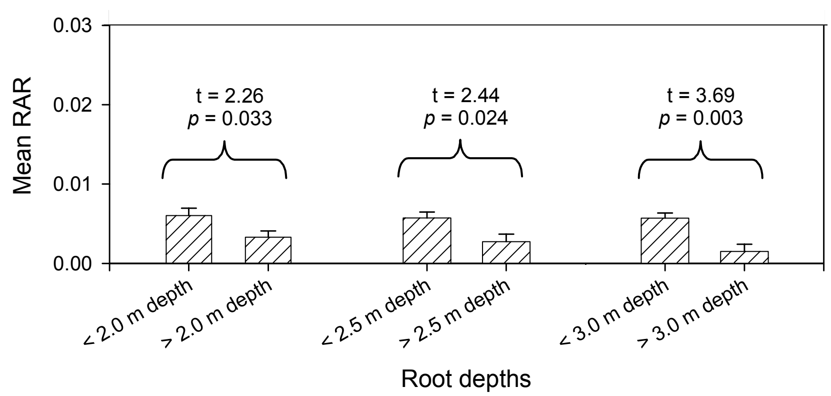


Figure 5.16 – RAR ($\bar{x}$ ± SE) of vegetated wet-dry tropics sites above and below indicated depth demarcations.

Results of *t*-tests between RARs of the different depth groups are shown.

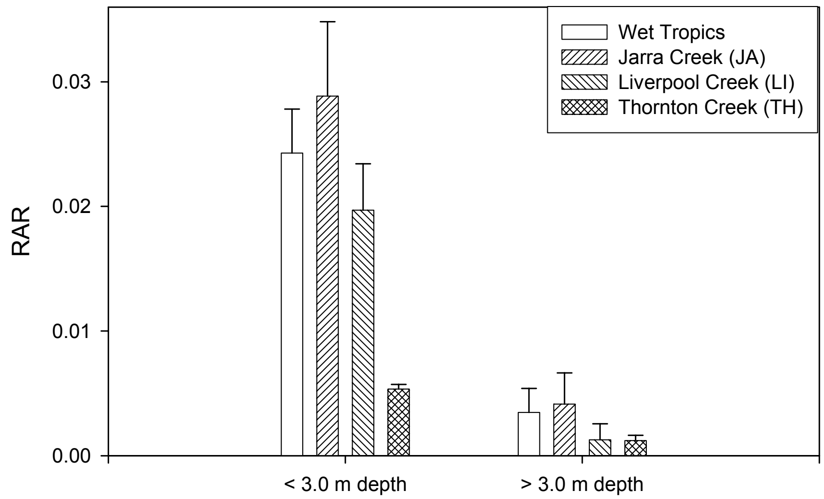


Figure 5.17 – RAR ($\bar{x}$ ± SE) at depths above and below 3.0 m depth.
Results for ANOVA for < 3.0 m depth: $F_{2,119} = 13.863$, $p < 0.001$; Tukey's test: JA-LI – $p = 0.18$, JA-TH – $p < 0.001$, LI-TH – $p = 0.007$. Results for ANOVA for > 3.0 m depth: $F_{2,36} = 1.234$, $p = 0.303$.

5.3.6 Factors influencing erosion

The first four axes of the PCA performed on the wet tropics data account for 84% of the variance in the data set of erosion driving forces (Table 5.1). Axis 1 groups bank structure and composition parameters, including decreasing depth/increasing height above the toe, increasing clay content and decreasing sand content (Table 5.2). Axis 2 groups decreasing depth, increasing RAR and decreasing erosion, and thus represents the RAR variations with depth and associated erosion. Axis 3 relates to reductions in erosion and gravel content and increases in clay content, while increases in gravel and reductions in erosion and sand content account for Axis 4 variability. Axis 1 explains more then 37% of the variance, but Axes 2 and 3 are of most relevance to erosion as erosion is a major covariate of these two axes (Table 5.2). Figure 5.18 shows the relationship between Axes 2 and 3 and their relationship with erosion. It is evident from this figure that along Axis 2, erosion decreases with decreasing depth and increasing RAR while along Axis 3, erosion decreases with decreasing gravel and increasing clay content, indicating RAR and stratigraphic control of erosion. The relationship between erosion rate and Axis 3 is a moderate ($r^2 = 0.65$, $p < 0.001$) linear relationship. Its relationship with Axis 2 is more complex – as depth decreases and RAR increases linearly along Axis 2, erosion rate decreases in a more exponential fashion, conforming to the rational model below:

$$y = \frac{(0.26 - 0.03x)}{(1 + 0.82x + 0.19x^2)}.$$

Table 5.1 – Explanation of variance in the wet tropics data set identified in the PCA.

AXIS	Eigenvalue	% of Variance	Cumulative% of Variance
1	2.56	36.60	36.60
2	1.42	20.27	56.86
3	1.14	16.34	73.21
4	0.82	11.66	84.87
5	0.71	10.21	95.08
6	0.21	2.94	98.01
7	0.14	1.99	100.0

Table 5.2 – Variables loading on the first four eigenvectors in the PCA of the wet tropics data set. Significant variables are highlighted in bold face.

	Eigenvector			
Variable	**1**	**2**	**3**	**4**
RAR	0.07	**0.63**	-0.01	-0.06
Sand content	**-0.49**	0.20	0.03	**-0.56**
Gravel content	-0.23	0.09	**-0.70**	**0.57**
Height above bank toe	**0.53**	0.08	-0.28	-0.29
Clay content	**0.53**	-0.07	**0.33**	0.27
Depth	**-0.32**	**-0.51**	0.29	0.16
Erosion rate	0.17	**-0.53**	**-0.48**	**-0.42**

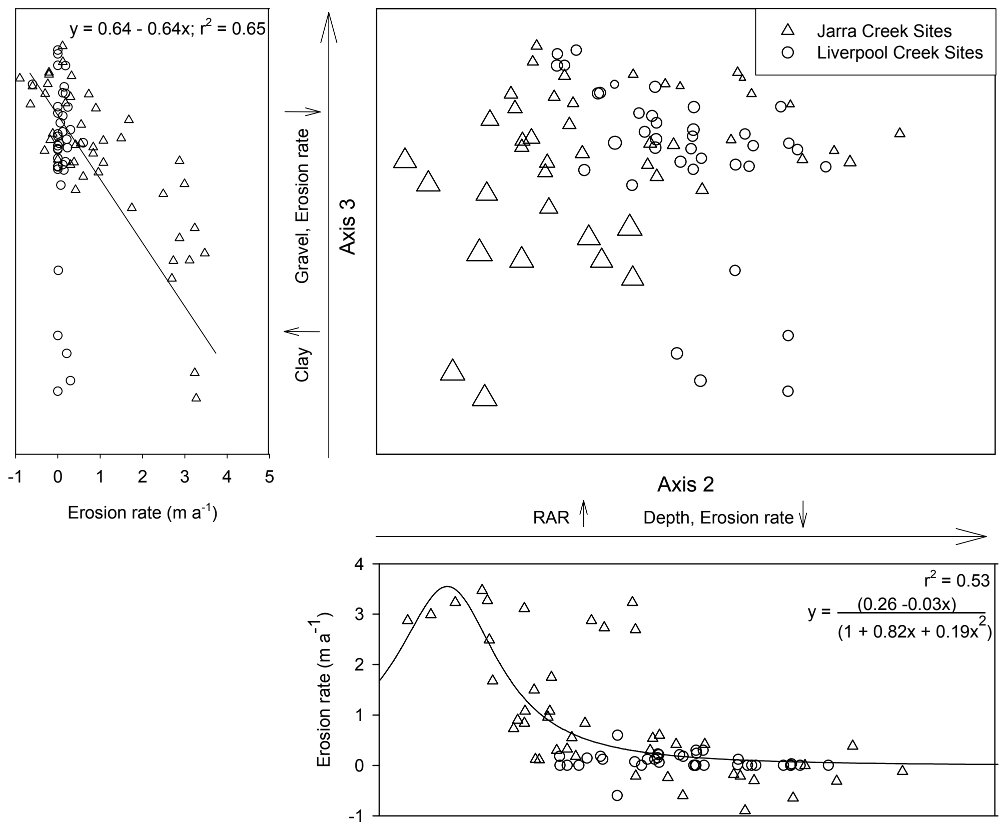


Figure 5.18 – Results of the PCA performed on the erosion-controlling factors in the wet tropics study sites.

In the main plot, the symbol size is proportional to the erosion rate. Variables that correlated strongly with each axis are indicated. In the side plots, relationships between erosion rate and the corresponding axis are illustrated and the appropriate regression model (if non-linear) is indicated.

The first four axes of the PCA of the wet-dry tropics data also explain most of the variance (Table 5.3). Axes 1 and 2 represent stratigraphic variability, with heights above toe (r = 0.5 and -0.35), depth (r = -0.53 and 0.33), sand content (r = 0.26 and 0.6) and clay content (r = -0.4 and -0.56) grouped on both axes. Axes 3 and 4 explain much of the variability in erosion rates between samples – again grouping RAR (r = -0.09 and 0.34) and gravel content (r = 0.75 and 0.5) with erosion (r = 0.62 and -0.62) on the two axes (Table 5.4). A plot of Axes 3 and 4 of the PCA, and the relationship between erosion rate and the axes, are shown in Figure 5.19. There was a moderate linear relationship between erosion rate and both Axis 3 ($r^2 = 0.42$, $p < 0.001$) and 4 ($r^2 = 0.34$, $p < 0.001$). Removal of the six outliers on Axis 3 improves this relationship considerably ($r^2 = 0.95$, $p < 0.001$). Interestingly, these outliers were located at only three sites (2 at each of TH0002, TH0007, TH0009), all of which were of Bank Type 4 and moved slowly (< 0.7 m a^{-1}) compared with other banks of the same type. While they appear to be outliers in the relationship between Axis 3 and erosion rate, these sites fit the relationship between gravel content and erosion rates (greater gravel content – less erosion). This relationship is explained further below.

Table 5.3 – Explanation of variance in the wet-dry tropics data set identified in the PCA.

AXIS	Eigenvalue	% of Variance	Cum.% of Var.
1	2.45	35.00	35.00
2	1.72	24.59	59.59
3	1.10	15.66	75.25
4	0.87	12.45	87.70
5	0.63	9.02	96.72
6	0.14	1.98	98.70
7	0.09	1.30	100.00

Table 5.4 – Variables loading on the first four eigenvectors in the PCA of the wet-dry tropics data set. Significant variables are highlighted in bold face.

	Eigenvector			
Variable	**1**	**2**	**3**	**4**
Gravel content	0.19	0.18	**0.75**	**0.50**
Erosion rate	-0.22	-0.12	**0.62**	**-0.62**
Height above toe	**0.50**	**-0.35**	0.02	-0.25
Depth	**-0.53**	**0.33**	-0.05	0.22
RAR	**0.40**	-0.23	-0.09	**0.34**
Clay content	**-0.40**	**-0.56**	-0.10	0.07
Sand content	0.26	**0.60**	-0.19	-0.36

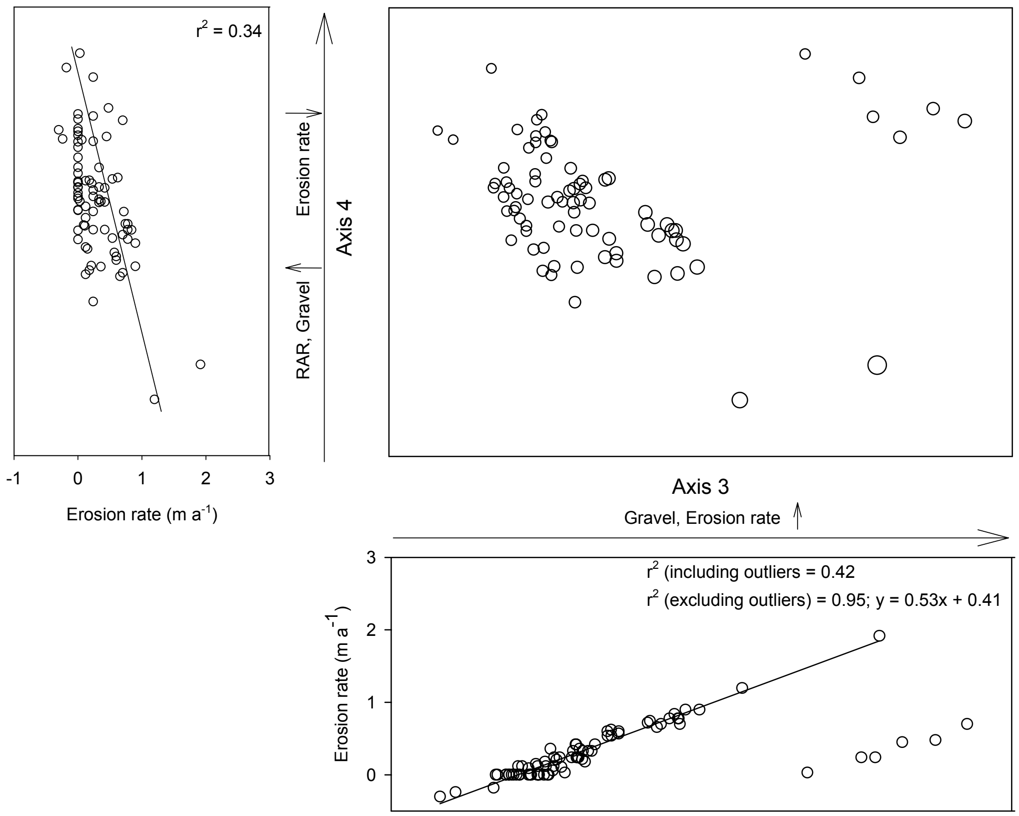


Figure 5.19 – Results of the PCA performed on the erosion-controlling factors in the wet-dry tropical study sites.

In the main plot, the symbol size is proportional to the erosion rate. Variables that correlated strongly with each axis are indicated. In the side plots, relationships between erosion rate and the corresponding axis are illustrated.

Both PCAs identified RAR and streambank gravel content as predominant covariates with erosion. In the wet tropics, clay content (Axis 3: r = 0.33) and depth (Axis 2: r = -0.51) of the sediment were also grouped with erosion rate (Axis 2: r = -0.53; Axis 3: r = -0.48) on separate axes, so their effects were investigated further. Scatter plots of wet tropics data showed non-linear relationships in which retreat rate maxima decreased exponentially with increasing RAR and gravel content (Figure 5.20 and Figure 5.21). Outliers in both relationships were excluded from the analysis. In the case of the gravel-erosion relationship, there were only two outliers, both from the same site (JA0003) – a site with a steep bank, the stability of which was affected by the sandy-gravel lower stratum resting at its angle of repose. Thus it was more easily erodible because there was no cohesion at all. In the RAR-erosion relationship, all outliers represented positions down the bank at only one particular site (JA0006) which had dense root networks, but failed after prolonged undercutting of the rootball. Thus, while the root networks were improving stability in the upper bank, they had little influence on overall retreat because there were no roots at the bank toe. Further, the undercutting of the rootball resulted in trees falling into the stream and concomitant failure of a large block of bank material. This exaggerated the actual retreat rate of the bank.

To examine the relationship between gravel and maximum erosion rate, measures of erosion rate were grouped according to the corresponding gravel content value. Group intervals of 5% gravel content were established after an initial group between 0 and 0.01. The maximum erosion rate within each group and its corresponding gravel content value were identified and the regression was performed on those values. This allowed identification of decreases in maximum erosion with increases in gravel content. In cases where no sample was recorded within a particular group, this group was excluded. Therefore, the groups were delimited by the gravel content values of 0, 5, 10, 15, 30, 35, 40, 45 and 60. The maximum erosion rates followed a four-parameter rational model (Figure 5.20) with maximum rates slowing exponentially with increases in gravel content within the bank, as outlined below:

$$y = \frac{(3.47 + 15264.7x)}{(1 + 10106.7x - 2001.64x^2)}.$$

The relationship between RAR and maximum erosion rate was examined in a similar fashion, with erosion rates grouped according to their corresponding RAR measure. Groups were established at an RAR interval of 0.005 after an initial group of 0-0.001. The maximum erosion rate within each group and its corresponding RAR reading were identified and the regression was performed on those values. Again, RAR groups for which no sample existed were excluded. Thus, the groups were delimited by 0, 0.005, 0.01, 0.015, 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, 0.055, 0.065, 0.07, 0.085, 0.115 and 0.12. Maximum erosion rate followed a four-parameter rational model (Figure 5.21) with exponentially decreasing erosion associated with increasing RAR:

$$y = \frac{(3.43 - 129.25x)}{(1 + 661.85x - 26463.5x^2)}.$$

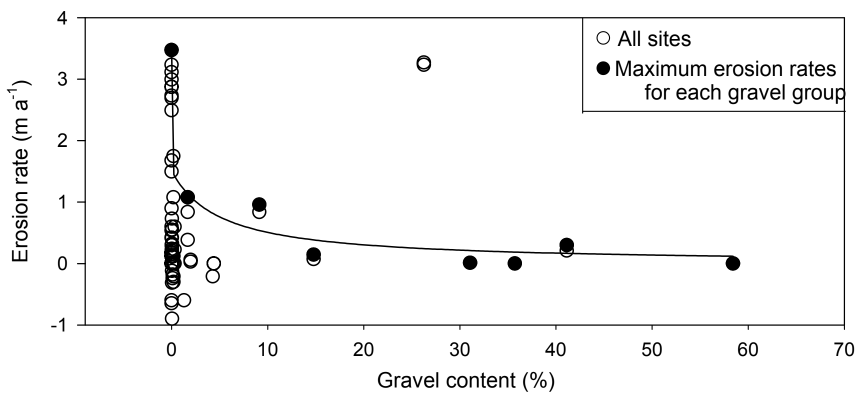


Figure 5.20 – Scatter plot between bank gravel content of the sediment and erosion rates of wet tropics streambanks, showing the significant rational relationship (r^2 = 0.96, *p* = 0.002) between gravel content and maximum erosion rates.

Note that negative erosion rates represent accretion.

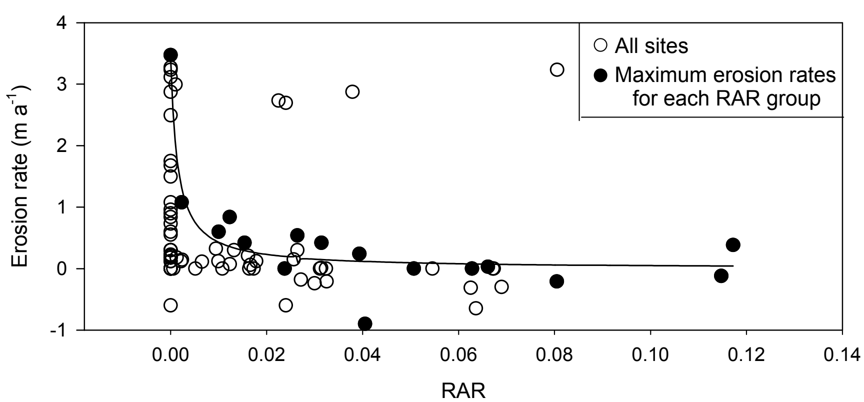


Figure 5.21 – Scatter plot between RAR values and erosion rates of wet tropics banks, showing the significant exponential decay relationship (r^2 = 0.87, *p* < 0.001) between RAR and maximum erosion rates.

Note that negative erosion rates represent accretion.

In the wet-tropics streams, there was no significant relationship between erosion and clay content or depth despite their identification as possible erosion correlates (Figures 5.22 and 5.23). A *t*-test of erosion rate between high (> 3.0 m) and low (< 3.0 m) depths also showed no significant differences between groups ($p = 0.257$, $t = -1.16$), despite RAR differing significantly between the same depth groups ($p = 0.001$, $t = 3.68$; see Figure 5.15).

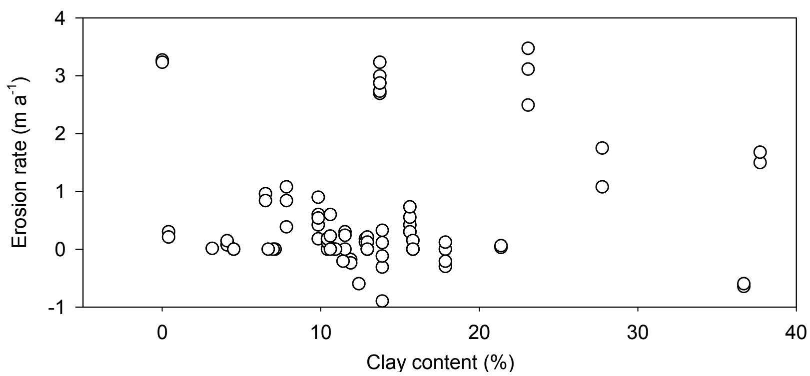


Figure 5.22 – Relationship between clay content and erosion rates of wet tropics sites.

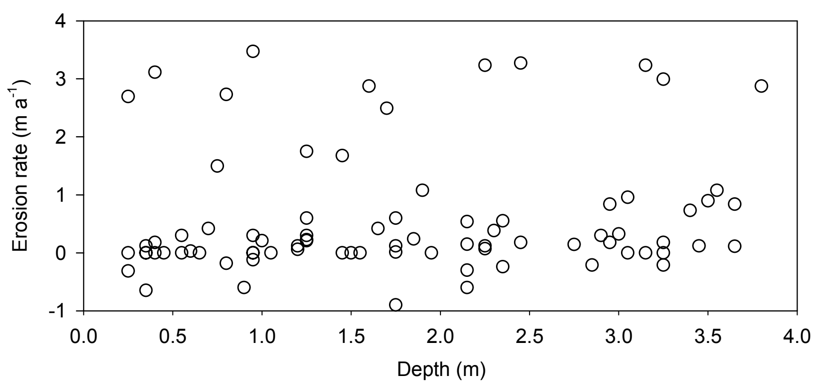


Figure 5.23 – Relationship between depth below bank top and erosion rates of wet tropics sites.

Scatter plots of wet-dry tropics data showed similar (though weaker) results to the wet-tropics data. General declines in maximum erosion rates were evident in association with both gravel content and RAR (Figure 5.24). To investigate this relationship, erosion rates were grouped according to their respective gravel content readings. Groups were established at intervals of 0.05% with an initial group of 0-0.001. Thus, the groups were delimited by the following gravel content values: 0, 0.05, 0.1, 0.25, 0.3, 0.4 and 0.45. The single maximum erosion rate readings in each group and their corresponding gravel content readings were then regressed to identify how maximum erosion rates decreased with increasing gravel. The relationship followed the exponential decay model:

$$y = 0.25 + 1.35e^{-10.25x} .$$

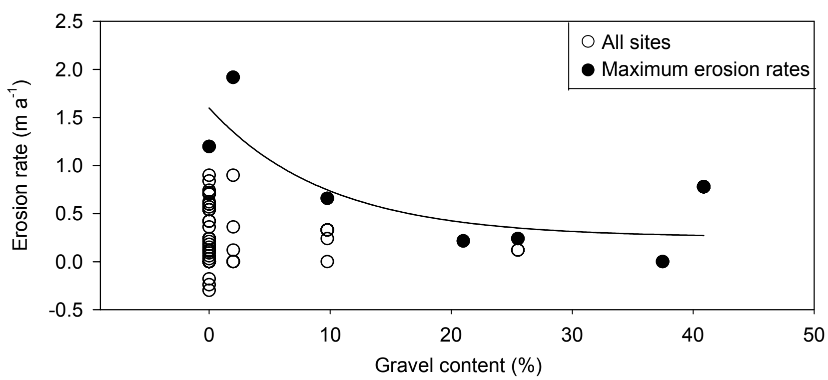


Figure 5.24 – Scatter plot between bank sediment gravel content and erosion rates of wet-dry tropics banks, showing the exponential decay relationship (r^2 = 0.67, *p* = 0.1) between them.

For the RAR-erosion rate relationship, groups were established at intervals of 0.001 from 0 to a maximum of 0.011 to identify the decreases in maximum erosion rate with increasing RAR. The relationship followed the rational decay model (Figure 5.25):

$$y = \frac{(1.97 + 338.33x)}{(1 + 938.81x)} .$$

Thus, there are strong relationships between erosion and RAR and sediment size in both regions.

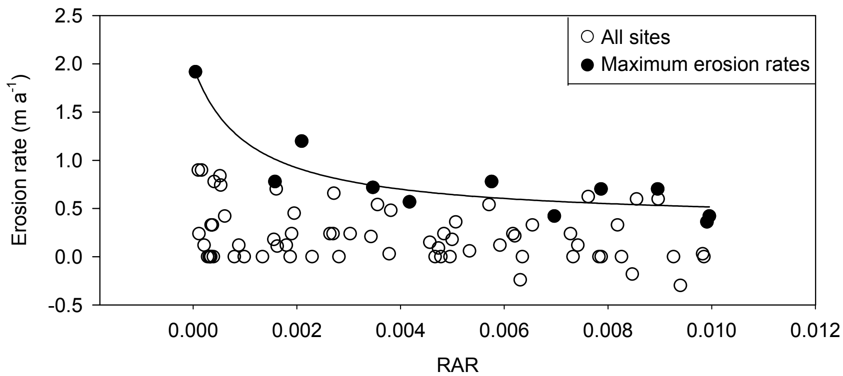


Figure 5.25 – Scatter plot between RAR values and erosion rates of wet-dry tropics banks, showing the significant rational decay relationship (r^2 = 0.85, p < 0.001) between RAR and maximum erosion rate.

5.4 Discussion

5.4.1 Root area ratios

RARs of vegetated sites within the three study streams varied between 0.00 and 0.12 ($\bar{x}$ = 0.02, SE = 0.003) and were therefore considerably higher than any reported in the literature. The wet tropics RAR values were particularly high and variable (0.00-0.12). The maximum RAR reading in Thornton Creek (wet-dry tropics) was 0.0099, which conforms with previous research. Reported RAR rates tend to be less than 0.01, regardless of region, vegetation type or species. A maximum of 0.0076 was reported for *Eucalyptus camaldulensis* and *Melaleuca ericifolia* on the Latrobe River, Victoria (Abernethy 1999), a maximum of 0.0093 was measured in forested areas in the Idaho Rocky mountain region (Simon and Collison 2002) and a mean RAR of < 0.001 was measured in northern Mississippi (Simon and Collison 2002).

While most comparable research has been conducted in temperate regions, research in tropical environments suggests high variability of forest root densities, in agreement with this study. Vogt *et al.* (1985), for example, noted that tropical evergreen forests had more fine roots than cold temperate deciduous forests (4070 g m^{-2} *vs.* 140 g m^{-2}), and Gower (1987) observed much lower fine root densities of 125 g m^{-2} in Costa Rican lowland forests.

The unusually high RARs encountered in the wet tropics streams in this study were partly due to several methodological differences between this study and others. Firstly, larger roots (> 20 mm) were included in the RAR measurements. Most studies of roots and their contribution to bank stability focus on roots < 20 mm in diameter, as the effect of larger roots on bank cohesion is considered to be negligible (Abernethy 1999, Coppin and Richards 1990). However, larger roots also play an important role in directing flow away from the bank and protecting sediment particles from direct flow (Thorne and Furbish 1995), so they were included in the analysis. The occurrence of roots larger than 20 mm at most vegetated wet tropics sites in this study resulted in high RAR values.

Secondly, the inclusion of all individuals in the riparian community in the RAR calculation resulted in a combined community RAR, which would be much higher than those calculated for specific individual trees, except in monocultures. This allowed comparisons to be made between RAR and community vegetation characteristics and analysis of community root influence on erosion rate, unlike previous research that has focussed on the RAR of particular species/individuals (e.g. Abernethy and Rutherfurd 2001, Simon and Collison 2002).

5.4.2 Root area ratio relationships with above-ground vegetation characteristics

RAR at shallow depths was related to above-ground vegetation density. The predictive capability of vegetation density for RARs was only moderate (r^2 = 0.42 at 1.0 m depth) and declined with depth (r^2 = 0.39 at 2.0 m; r^2 = 0.26 at 3.0 m), but it does suggest some similarity between above- and below-ground characteristics. Community density and medium-sized root density at depths greater than 0.3 m have been shown to be strongly correlated (Wynn *et al.* 2004) and higher root concentrations have been attributed to closer tree spacing (Yim *et al.* 1988). However, few studies report on this relationship for greater depths. Nevertheless, wide and dense riparian strips are often discussed in stream management contexts as being beneficial to streambank stability (Bren 1993). Data from the three sites of this study concur with this suggestion as increased vegetation densities mean increased RAR and increased potential for erosion resistance, at least in the upper profile. However, at the bank toe, where extra stability and cohesion are arguably most important, vegetation density provides poor predictive power.

The relationship between vegetation height and maximum RAR (at 1.0 m depth) identifies low RARs in communities with low crowns, and highly variable RARs with much taller vegetation. While many researchers have shown strong correlation between tree height and root morphology, there are no reports of relationships with the maximum, as reported here. Furthermore, most studies focus on total root numbers and biomass and ignore the impact of variations in root density on height. There are strong positive linear relationships between the height of *Fagus sylvatica* L. and its fine and total root biomass (Curt and Prévosto 2003) and similar relationships between height and root numbers in *Larix leptolepis* (Bending and Moffat

1999). The relevance of total biomass to streambank erosion is, however, limited, as it does not account for variations in RAR with depth.

The relationship between tree height and maximum RAR at a depth of only 1.0 m suggests that the predictability of basal RAR from tree heights is poor. Only maximum estimates of root densities are possible, due to the suite of factors that appear to influence RAR variability. This predictive capability for RAR diminishes at greater depths, largely because of the rapid decline in RAR below 2.0-3.0 m.

Diameter at breast height (DBH) was a poor predictor of RAR at any depth ($r^2 < 0.05$ for all depths), in contrast with published data that suggests otherwise. For example, Drexhage *et al.* (1999) showed a strong positive linear relationship between DBH and root biomass of sessile oaks. Positive logarithmic relationships have also been shown to exist between DBH and below-ground biomass of *Fagus sylvatica* in France and Germany (Bolte *et al.* 2004, Curt and Prévosto 2003, Le Goff and Ottorini 2001). Similar results have also been found in Australian eucalypt species (Eamus *et al.* 2002). However, all of these examples have viewed root architecture on an individual basis, not as a community. RAR was determined by totalling the area of roots, while DBH was a mean measure of community DBH. Thus, comparisons between the two measures are complicated. Riparian vegetation communities consist of trees of mixed species and ages. DBH varies accordingly and mean DBH is influenced more by outlying large/small individuals than are combined RARs. Lin *et al.* (2005) observed similar results in a subtropical forest in Taiwan, failing to identify any relationship between DBH and community fine root density. Thus, DBH does not provide any insight into the potential of a vegetation community to assist in bank stability.

The analyses of RAR in relation to vegetation characteristics have shown that above-ground vegetation measures are not useful in gauging below-ground morphology in the three study streams. Even in the RAR relationships with tree height and vegetation density, satisfactory predictions of RAR could only be made at low depths.

5.4.3 Root area ratio relationships with depth and sediments

RAR and depth

There was a general decline in RAR with depth and a predominance of roots in the upper portions of the bank; however, these results differ from reported RARs in two respects. Firstly, the decline was not as pronounced as in previous research because, although there was a general decline at most sites, the root profiles were evidently more variable than previously reported (RARs of 0-0.12 cf. 0.00001-0.0076 reported by Abernethy 1999). Secondly, the maximum depth of root occurrence was much deeper than the 0.5-1.0 m reported in the literature (Abernethy and Rutherfurd 2001, Canadell *et al.* 1996, Gray and MacDonald 1989, Jackson *et al.* 2000, Jackson *et al.* 1996).

Comparisons between previous studies and this one are complicated by the different climatic regimes that tropical trees are exposed to. However, even tropical examples suggest root habits that contrast with the results of this study – root density has been shown to be greatest within 0.3 m of the surface and to decline consistently with depth (Akinnifesi *et al.* 1999, Lin *et al.* 2005). This contrasts with the highly variable RAR values measured in this study (0 – 0.12) in the upper 3.0 m of the vegetated banks and a marked drop in RAR below this point. These differences are largely due to the complications provided by bank angle and 'community RAR'. Banks are complicated because they are not level surfaces. On gradually sloping banks, lateral roots have the ability to stretch down the bank, while effectively not being any deeper. Thus, RARs can remain high even at greater depths, in the absence of any other impedance. The calculation of RAR at the bank face in this study highlights the impact of bank features on RAR. This is rarely encountered in other studies as RAR has commonly been determined away from the bank-channel interface (e.g. Abernethy 1999).

The higher and more variable community RARs measured in this study are also partly due to the unavoidable inclusion of various species of unknown age located at varying distances from the established root profiles (see Abernethy 1999 for comparison). RARs are known to vary between species and individuals of different ages and with distance from the trunk (Abernethy 1999, Akinnifesi *et al.* 1995, Drexhage *et al.* 1999, van Noordwijk and Purnomoshidi 1995). Drexhage *et al.* (1999), for example, measured significant differences between mean root cross-sectional area of differently aged stands of *Quercus petraea*; Akinnifesi *et al.* (1999) observed significant differences in root abundance between several species in Nigeria; while Sudmeyer *et al.* (2004) observed that root density logarithmically declined with distance away from the trunk.

Regardless of these differences, RAR trends with depth were evident. Variable RARs were a common trait in the upper 2.0-3.0 m, and RARs were significantly lower below this point. These traits were similar in both wet and wet-dry tropical streams.

<u>Effect of water availability on root depths</u>

The availability of water in a bank and the level of waterlogging that occurs in riparian zones is a major influence on root depths (Bennie 1991, Canadell *et al.* 1996, Coutts and Philipson 1978, Dennis *et al.* 1978). The obvious differences in RAR above and below the 2.0-3.0 m demarcation in this study suggest that waterlogging becomes an issue around this zone. The permanent saturation of portions of wet tropical streambanks, due to the perennial nature of rivers and streams in the region, support this suggestion. No piezometer data are available for any of the study sites, but the distinct lack of roots below 3.0 m in wet tropics sites, regardless of sediment type or any other local factor, also concur with this suggestion ($RAR_{<3.0} = 0.04$; $RAR_{>3.0} = 0.006$; $p < 0.001$). Similar suppression of root growth by saturated bank material has been observed elsewhere in Australia, with *Eucalyptus nitens, E. globulus*, *E. camaldulensis* and *Melaleuca ericifolia* all having less dense root networks in saturated sediment (Abernethy and Rutherfurd 2000a, Moroni *et al.* 2003).

Given the ephemeral presence of water in wet-dry tropical streams, deeper root systems were expected in this region than the wet tropics. The wet-dry tropics RAR readings significantly declined at a depth of 2 m, suggesting shallower root networks. However, the depth-averaged RAR graphs and site-by-site root profiles (Figures 5.5 and 5.13) showed that while RAR significantly declined at shallower depths in the wet-dry tropics than the wet tropics banks, maximum root extent was actually much deeper. Thus, the earlier significant decline in RAR is a reflection more of the lower vegetation density in the wet-dry tropics than an indication of any waterlogging suppression.

<u>Effects of sediment on root depth</u>

RAR variability appeared to decline with increasing gravel content in all of the study banks. However, this relationship was not shown to be significant, largely due to the masking relationships between RAR and depth and bank saturation (Section 5.3.3). Larger sediment particles (as well as bed rock and hard clay deposits) provide mechanical barriers to root growth (Bennie 1991, Canadell *et al.* 1996). Root development of *Larix leptolepis*, for example, has been shown to be restricted by sedimentary units composed of cobbles (Bending and Moffat 1999). Most sedimentary units with large gravel constituents were located at or near the bank toe (Table 4.1, e.g. JA0003, JA0010, LI0004, LI0006, LI0007), where the influence of depth and water is also most prevalent. It is thus likely that the RAR of streambanks in this study are less variable at greater depths because of the restricting influence of bank saturation and bank material composition.

5.4.4 Erosion variations

No direct relationship between RAR and erosion values was identified in this study, but there was a relationship between maximum erosion rates and RAR in both wet and wet-dry tropics streams. A range of erosion rates can occur at low RARs with variance explained by other local factors. However, higher RAR reduces this variability and restricts erosion rate, such that maximum rates decrease exponentially with increasing RAR. Roughness provided by bank roots slows primary flow adjacent to the bank face and weakens secondary circulation, resulting in erosion reductions (Thorne and Furbish 1995). Roots also contribute to soil binding and aggregate stability in sediment (Jastrow and Miller 1991, Lister *et al.* 2004, Miller and Jastrow 1990) and improve sediment cohesion and strength (Ekanayake and Phillips 1999, Waldron and Dakessian 1981, Wu *et al.* 1979).

Maximum erosion rate also declined exponentially with gravel content. The non-cohesive nature of all of the strata with higher gravel content normally makes them more susceptible to entrainment. The absence of roots in gravel-dominated strata in the wet tropics (RAR variability was shown to decrease markedly in sediment with greater than 5% gravel) also meant greater susceptibility of these strata to erosion. However, entrainment of coarser sediment typically requires high velocities (Andrews 1984, Hjulström 1935). Thus, the anomalous low levels of erosion in the gravel-dominated strata in this study can be attributed to the low magnitude and short duration of the flows of the 2003/2004 wet season that were unable to perform significant geomorphic work on this larger sediment. The absence of any clay-dominated bank sedimentary units (Figure 4.4) may also affect the results – more clay-dominated banks may have provided more resistance against erosion and altered the gravel-erosion relationship. The interconnected nature of these relationships (high gravel – low RAR and erosion; high RAR – low erosion and gravel) also explains much of the variability in the data. These parameters affect erosion rates independently and thus may independently cause erosion in different banks.

The depth of the point of scour and scour rate were grouped together by the PCA. However, despite relationships existing between erosion and maximum values of RAR and gravel and obvious differences in RAR (in both wet and wet-dry tropics) and gravel (dry tropics) existing with depth, the scatter plots show no difference in erosion with depth regardless of RAR or gravel content in either the wet or wet-dry tropics. This erosion-depth relationship is thus masked by the concurrent decline in RAR and increase in gravel presence with depth. Nevertheless, given the obvious decline in maximum RAR with increasing depth, there is greater potential for higher rates of erosion due to the lack of protection by roots, irrespective of the absence of any direct depth-erosion correlation. High RARs throughout the bank are beneficial for stability (Thorne 1990). However, trees are only capable of stabilising steep banks up to 3.0 m high due to the effects of bank saturation on root distribution (as discussed above) (Rutherfurd *et al.* 2000). Below this depth, RAR is too low to provide any benefits. Given the height of most banks in this study, this point is especially relevant – the lack of roots at the bank toe reduces the stabilising effect of any dense roots in the upper portion of the profile and masks any depth-erosion relationship. Thus, regardless of depth, portions of the bank face are more likely to erode at greater rates if they have low gravel content or low RAR.

Wet and wet-dry tropics sites display different relationships, with erosion rates at wet tropics sites showing far more variability than wet-dry tropics sites. The identification of specific stream power as a major correlate with erosion in Chapter 4 suggests that these differences between regions are related to their different hydrological regimes. However, the more variable nature of RAR in the wet tropics streambanks may have also contributed to this. This variability reflects the different climatic and edaphic controls at play in the two regions and suggests that bank erosion and retreat management should consider these differences in conjunction with other driving forces. Other factors are as important in controlling bank stability (bank geometry, curvature and specific stream power were shown to explain bank retreat variance and gravel was shown to be linked with bank face erosion); however, an understanding of RAR relationships with these factors as well as their variation due to differences in water and nutrient availability is vital in understanding why particular banks will retreat or erode.

5.5 Chapter summary

While differences existed between wet and wet-dry tropics streams with regard to erosion rate relationships, overall root densities and density variations due to variations in local factors, there were similar findings for the two regions. Thus, with regard to the initial questions, 1) there are significant relationships between RAR and both tree height and community density; 2) there are significant differences in RAR with depth; 3) there are significant differences in RAR between a wet-dry tropics stream and two wet tropics streams; and (4) both RAR and gravel content of bank sedimentary units are significantly related to scour up the bank.

CHAPTER 6
SUMMARY AND CONCLUSIONS

6.1 Background and findings

Erosion rates vary between and within climatological regions. Hooke (1980) and Lawler (1993a) both identified variation in erosion rates, due to variable effects of local and regional driving forces. They noted, though, that regardless of this variation, there were linearly increasing trends in the log of bank retreat rates with the log of both channel width and drainage area (Chapter 1). This study measured bank retreat rates in two wet and one wet-dry tropics stream to determine whether rates conformed to the worldwide relationships between retreat, channel width and drainage area identified by Hooke (1980) and Lawler (1993a) (Chapter 3). Rates were also compared to streams of similar size in other climatological regions. Results from the three study streams were compared with each other to determine whether more local climatological and hydrological differences impacted upon bank retreat rates.

Bank retreat rates of the 34 study banks conformed to general channel width and drainage area relationships discussed in Chapters 1 and 3, regardless of the unique hydrology and climate of the wet and wet-dry tropics. These comparisons must be made cautiously as they are only valid as far as the datasets of differing quality and quantity allow. Rates were also similar to streams of similar size elsewhere, but low in comparison with streams within similar climatological regions. Most of the studies listed in Chapter 1 occurred over several return periods, as opposed to this study which was restricted to one wet season. Nevertheless, small north-eastern Queensland streams do not necessarily move at great rates. While stream power, flood frequency and annual flows may be greater than in temperate counterparts (McMahon *et al.* 1992), these streams appear to be adapted to these conditions, exhibiting higher disturbance thresholds (Pearson 1999). The lack of any apparent relationship between retreat rates and climatological or hydrological regimes results from greater variation within regimes and streams than between regions.

This study examined the erosional response of wet and wet-dry tropics streambanks to several local driving forces. Models of streambank erosion generally identify a suite of factors that act together to affect erosion rates – a trend that can be ascribed to the largely heterogeneous nature of streams. While all parts of a stream are interconnected, stream processes and local characteristics vary considerably over short distances. Thus, it is rare that single factors act solely to control rates of bank retreat. This concept complicates the analysis of erosion rates and, therefore, the development of erosion management plans. It is difficult to put plans in place to reduce erosion in multiple locations when erosion will vary considerably between sites with different predominant driving variables.

Bank sedimentology and stratigraphy can be a major control of bank retreat: for example, Dapporto *et al.* (2003) identified it as part of a complex combination of factors that affect retreat. Similarly, Thorne and Tovey (1981) noted that it determined resistance to fluvial scour and Huang and Nanson (1998) showed that it controlled channel cross-sectional area. This study identified little sedimentological or stratigraphic influence on bank retreat rates. There was some suggestion that the presence of a coarse sedimentary unit at the bank toe resulted in increased bank retreat (some banks of Type 4 – heterogeneous with a coarse lower/middle layer – experienced > 3 m of bank face erosion during the study period), but these results were inconclusive. However, despite the considerable stratigraphic variation of the 34 study sites, gravel content was observed to have some control over erosion rates. Given the lack of any relationship between overall bank retreat and sedimentology or stratigraphy, the effect of gravel in controlling erosion rates is noteworthy. It is probable that the study period was too short to see the effects on overall retreat – that is, erosion rates were affected by gravel content, but the bank top did not at that stage respond to erosion closer to the toe.

Root area ratio, as an indication of root density provides an indication of the resistance that vegetation will provide a bank to retreat and instabilities. Higher root densities are responsible for slower bank retreat (Wynn *et al.* 2004). As discussed in Chapter 5, this is largely because RAR is an important factor in mechanical reinforcement of the bank (Abernethy 1999), it provides resistance against primary and secondary flow (Darby 1999) and it assists in aggregation of bank sediments (Jastrow and Miller 1991). While these direct relationships were not examined in this thesis, the relationship between RAR at different depths and bank retreat, and the contribution of RAR to the control of erosion at different bank heights, were investigated.

Maximum bank angles are controlled by RAR at the bank toe. Dense root networks below 3.0 m provide protection against shear stresses provided by direct and secondary low and high flows. Gradually sloped banks still occur without root protection; however, maximum possible angles are much greater on these banks without trees. The relationship identified between bank angle and maximum bank retreat rates (Chapter 4) indicates that RAR has indirect control over retreat rates.

Stream power (and other hydrological characteristics), curvature, bank geometry, channel dimensions, discharge and catchment area are all factors that have been shown to control retreat and scour rates to some degree. Abernethy and Rutherfurd (1998), Hooke (1980) and Laubel *et al.* (2003) measured relationships of varying strength and importance between stream power and bank retreat rates. Hickin and Nanson (1984) and Hudson and Kesel (2000) identified separate curvature models explaining bank retreat. Abernethy (1999), Dapporto *et al.* (2003) and Laubel *et al.* (2003) also identified a strong relationship between bank geometry and retreat rates and mechanisms. RAR and bank sediment characteristics were the main focus of this study, but due to the natural variability of characteristics between study sites, all other hydrological, geomorphological and vegetative characteristics were included in the analysis to determine if they influenced either bank retreat or localised scour/instabilities.

Subtle differences in local erosion-driving forces between sites can complicate erosion monitoring and development of management plans. Direct relationships between variables are difficult to establish, due to the scatter created by the assortment of active erosion driving forces. However, the identification of absolute threshold levels of active driving forces is just as useful. Thresholds are an important concept in stream erosion studies. They provide an indication of the resilience of certain banks to disturbance and tell us when changes might take place. Stream geomorphological thresholds have been reported with regard to particular magnitudes, frequencies and durations of flows that are required to perform enough work to exceed these thresholds (Andrews 1994, Baker 1977, Erskine 1996, Wolman and Miller 1960). This study sought absolute thresholds of the erosion driving forces to identify the point at which erosion or bank retreat started to occur.

Important thresholds were found for some erosion driving forces. While specific stream power, bank height and angle and curvature were not directly related to overall bank retreat, thresholds were established for each variable. Retreat was more variable at high specific stream powers, on high, steep banks and at lower curvatures. Bank retreat was low until these thresholds were attained. Thresholds existed for curvature (< 2.0), bank height (> 3.2 m), bank angle ($> 45°$) and specific stream power (> 130 W m^{-2}). Once these thresholds were exceeded, variations in bank angle explained bank retreat variability. Thus, low banks with great curvature that were subject to low specific stream power retreated least; however, retreat of high banks with low curvature and high specific stream power was controlled by bank angle, with higher bank angles leading to greater retreat. Therefore, although relationships between these driving forces and erosion rates were complicated by the scatter in the data due to the variety of active driving forces, maximum retreat rates declined with increasing curvature and decreasing specific stream power, bank height and angle. These thresholds need to be tested in other north-eastern

Queensland streams of varying sizes and morphology to identify their relative applicability in this region.

Thresholds also existed for erosion rates at different bank heights. Maximum erosion rates were directly linked to both RAR and gravel content at the point of erosion. In both cases, erosion was highly variable in banks with low values for the respective variable, as erosion was explained by other variables. However, as RAR and gravel content increased, erosion variability reduced markedly. All of the sediment units measured in this study were of a sandy-gravel nature. Previous studies in this region have described similar sedimentary units (Anon 1996, Dalla Pozza 1999, Greenslade 2001, Jack 2001, Pearson 1999, Rogers *et al.* 1999). Thus, this result has much wider implications – while other variables will differ between sites and streams, the gravelly nature of many bank sedimentary units will govern, to some degree, rates of erosion.

Variations in root density throughout the bank, between streams and between sites on the same stream provide different stabilising effects and so can influence erosion and retreat rates. Analyses of these variations and what causes them are thus important for stability and erosion studies. Most RAR values reported in the literature range between 0.00 and 0.01 (Abernethy 1999). These figures tend to vary considerably with depth (Sudmeyer *et al.* 2004). Most previous research has shown a concentration of roots in the upper 0.3-1.0 m of bank (Bending and Moffat 1999, Sudmeyer *et al.* 2004, Wynn *et al.* 2004) and for bank stability purposes have an approximately 3.0 m vertical limit (Rutherfurd *et al.* 2000). Obvious variations in RAR have also been shown to exist according to vegetation characteristics, such as density, tree height and DBH (Bolte *et al.* 2004, Lin *et al.* 2005), levels of saturation (Bending and Moffat 1999, Coutts and Philipson 1978, Stone and Kalisz 1991) and with sediment type (Davis *et al.* 1983, Sainju and Good 1993). This study investigated root density dependence on depth, stratigraphy/sedimentology and vegetative factors to aid in identification of root-erosion relationships.

Root area ratios provided a good indication of root distribution throughout the soil and thus provided an indication to root contribution to increased stability and reduced sediment entrainment. The field results showed that:

- RARs were between 0.00 and 0.12 – higher and more variable than those reported elsewhere; this result was ascribed to the tropical environment, the influence of community RAR, the inclusion of all root sizes and the riparian setting;

- vegetation density and tree height were both related to RAR: there was a linear relationship between root and stem density which weakened with depth, while variability of RAR increased as average tree height increased;
- RAR was shown to generally decline with depth: RARs were variable in the top part of the bank (< 3.0 m depth), but generally decreased with increasing depth; this relationship was most conspicuous at a depth of 2.5-3.0 m;
- with respect to the upper 3.0 m of the bank profile, RAR was significantly greater in Jarra Creek and Liverpool Creek than Thornton Creek;
- RARs in all streams dropped noticeably at a depth of 2.5-3.0 m, but the demarcation was most marked in the wet tropics streams where dense RARs would be expected in the upper bank profile due to the availability of water and the denser riparian vegetation; the smaller decline in RAR with depth in wet-dry tropics streams suggests some degree of sediment saturation control of root growth; and
- sediment constituents or stratigraphy appeared not to affect root growth.

6.2 Further research

Due to the dearth of any previous substantial research on bank retreat and erosion problems in tropical regions, there is much research that can follow this project to extend our knowledge on tropical fluvial activity. Previous bank erosion research has focussed its attention on temperate regions where streamflow is often less variable and less hydrologically active than tropical flows (McMahon *et al.* 1992). Thus, banks are exposed to more consistent and less extreme flows. The different hydrological characteristics in the tropics means that streambanks need to adjust to different fluvial thresholds to resist erosion.

Abernethy and Rutherfurd (1998) contended that different bank retreat processes dominate at certain points along a stream. Using the Latrobe River as an example, they identified that subaerial processes were dominant in the upper reaches, scour dominated the middle reaches and mass failure processes were dominant in the lower reaches. This study identified three major retreat processes – scour, scour followed by slippage and cantilever failure. Cantilever failure and slippage mechanisms dominated with regards to severity, but scour was the most frequently occurring erosion mechanism. Given that this study only focussed on short reaches of the three study streams, all located within the mid-low stretches of the stream, no zonation of erosion mechanisms could be identified. Further studies of Jarra Creek, Liverpool Creek and Thornton Creek, as well as other streams in the region looking at the entire stream lengths would be useful to provide tropical comparisons with the findings of Abernethy and Rutherfurd (1998).

Larger streams tend to be subject to larger-scale hydrological and geomorphological processes and characteristics. Bank retreat rates tend to reflect this increase in channel and process scale. For example, rates of retreat are explained well by both channel width and catchment area (Chapter 1). This study focussed its attention on three middle-order streams, all of which were part of larger catchments. Research from this study could be extended to larger tropical systems to determine whether their rates of bank retreat similarly conformed to the relationship identified in Chapter 1.

The magnitude/frequency debate is central to many streambank retreat and erosion studies. Most research, however, focuses on the impact, or lack thereof, of larger magnitude events and ignores the effects of the low magnitude, highly frequent dry season flows. This study focussed on the effects of one particular wet season and so ignored the effects of the dry season flows. Although no flows occurred in the dry season in Thornton Creek, the perennial nature of Jarra Creek and Liverpool Creek raises the question as to the effectiveness of these flows in the wet tropics. Failed basal blocks provide protection for failed banks against these flows (see Darby *et al.* 2002, Ebisemiju 1994, Okagbue and Abam 1986, Thorne and Tovey 1981); however, their contribution to longer-term erosion and retreat rates needs to be investigated. A larger dataset is thus a high priority, especially given the variability of the wet seasons.

Moisture content and related pore-water pressures are important factors in consideration of bank stability and retreat. Wet tropical streams flow perennially and rain events are frequent. Thus, banks are subject to regular negative pore-water pressures associated with rapid drawdown effects and parts of the banks remain continuously wetted. While the effects of pore-water pressures are well-documented (see Abernethy 1999), the effects of perennial bank wetness are less well known. The effects of tropical vegetation (natural and agricultural) on bank wetting are also poorly understood. Given the proximity of agricultural land uses to the bank top at many locations in the wet tropics (often within 2.0 metres on Jarra and Liverpool Creeks), this information would be highly beneficial for stream restoration and rehabilitation practices.

6.3 Conclusion

Streambank retreat and scour can largely be manifested by a few major driving forces, but the interaction between these driving forces is complicated. The many human uses of floodplains, riparian zones and channels complicate these interactions further. There is a dearth of knowledge of these interactions in north-eastern Queensland (and the tropics in general), which is surprising considering the widespread clearance of floodplain vegetation in the region for agricultural land uses. Conflicts between human and natural stream values are common in this region, yet reasoning behind management decisions have for long periods been based on theories developed from research in temperate regions. Further research on fluvial-related topics in north-eastern Queensland is required to provide vital information for improved tropical land management practices.

This study suggests that specific stream power, curvature, gravel content, bank geometry and RAR are all factors that need to be considered in riparian/channel management. Although the first three factors are difficult to control, ensuring bank geometry and RAR thresholds are not exceeded may provide extra resistance to the effects of the first three factors. The implications of this research are especially important considering the low magnitude of the 2003/2004 event. An understanding that even smaller regular events have the potential to cause retreat of banks is important to promulgate to land managers.

Given the interconnection of toe RAR and bank geometry identified in this study and the relationship between vegetation and root density, rehabilitation of riparian lands appears to be a major concern. Increasing density means extra roots at the bank face which potentially means reduced bank angle and thus reduced bank retreat. However, it is necessary to recognise the importance of toe stability of high banks and the lack of natural protection provided to high, steep banks, even at densely treed sites. Although toe RAR and bank angle are linked, toe protection rarely existed in steep banks over 3.0 m in height. This creates hindrances for natural riparian rehabilitation and bank stabilisation. While hard engineering techniques are becoming less acceptable due to aesthetic and cost issues, in situations where conditions are not right for vegetation rehabilitation alone, a contribution of vegetation and engineering rehabilitation techniques should be considered to help enhance the coexistence of human and natural stream values.

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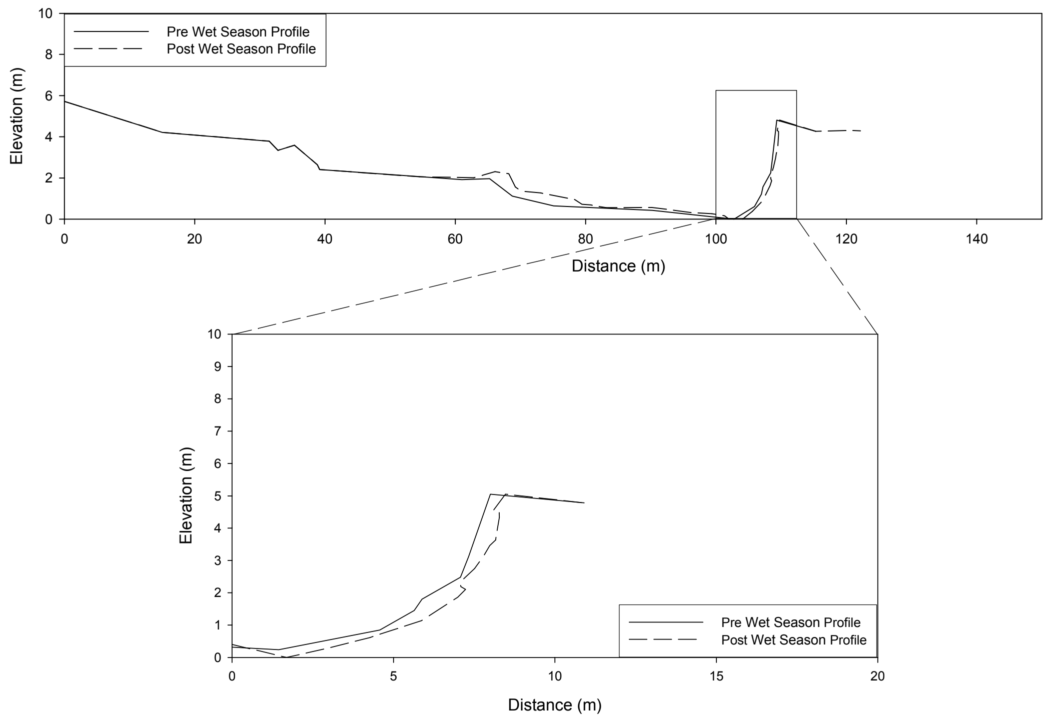
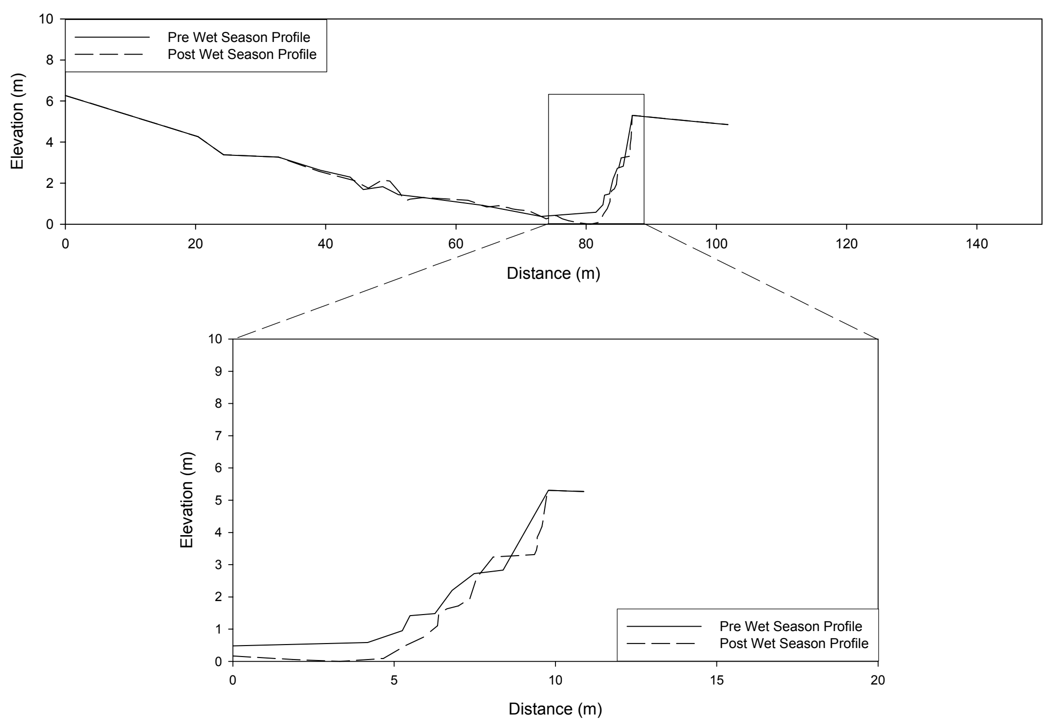
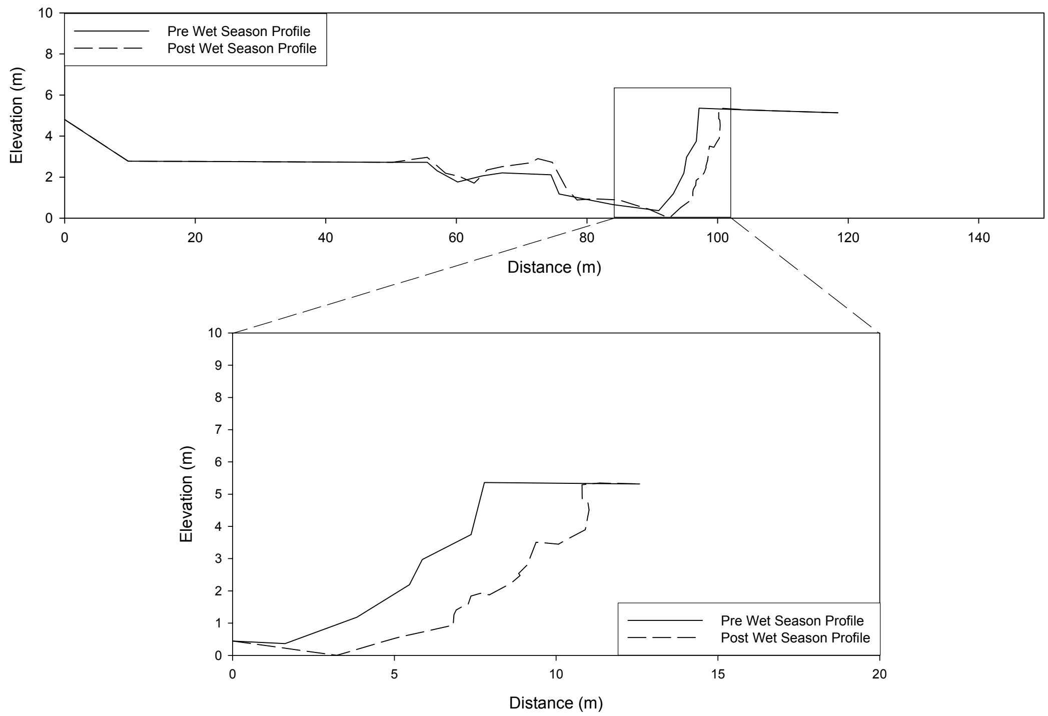
APPENDIX A



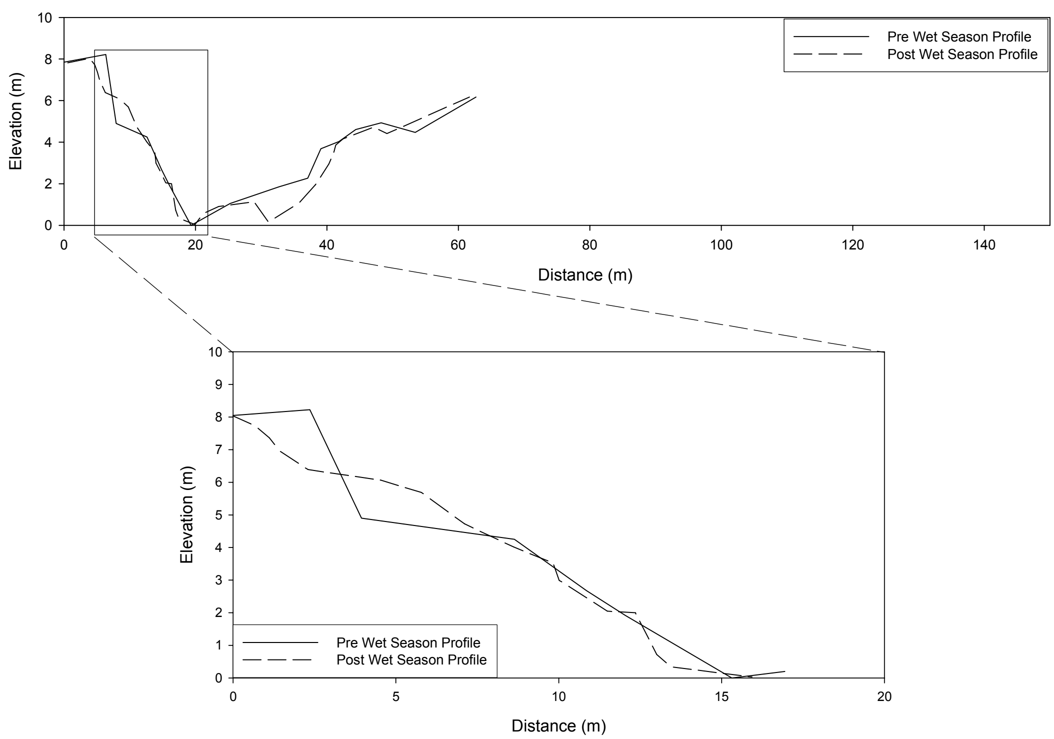
Appendix A.1 – JA0001 pre- and post-wet season channel and bank profiles.



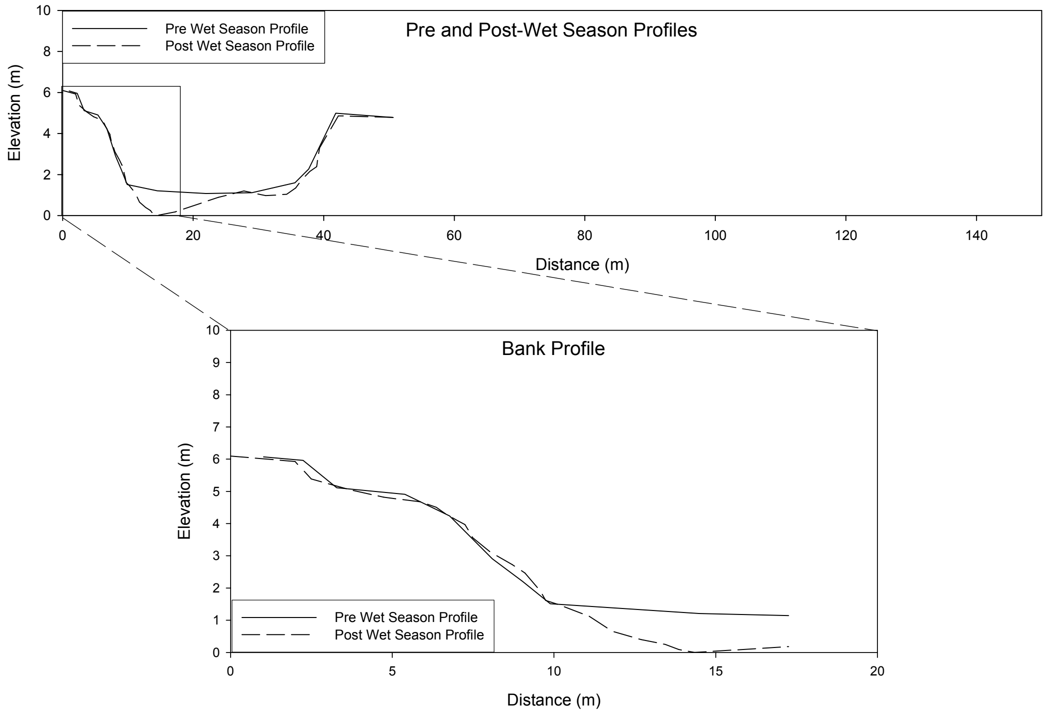
Appendix A.2 – JA0002 pre- and post-wet season channel and bank profiles.



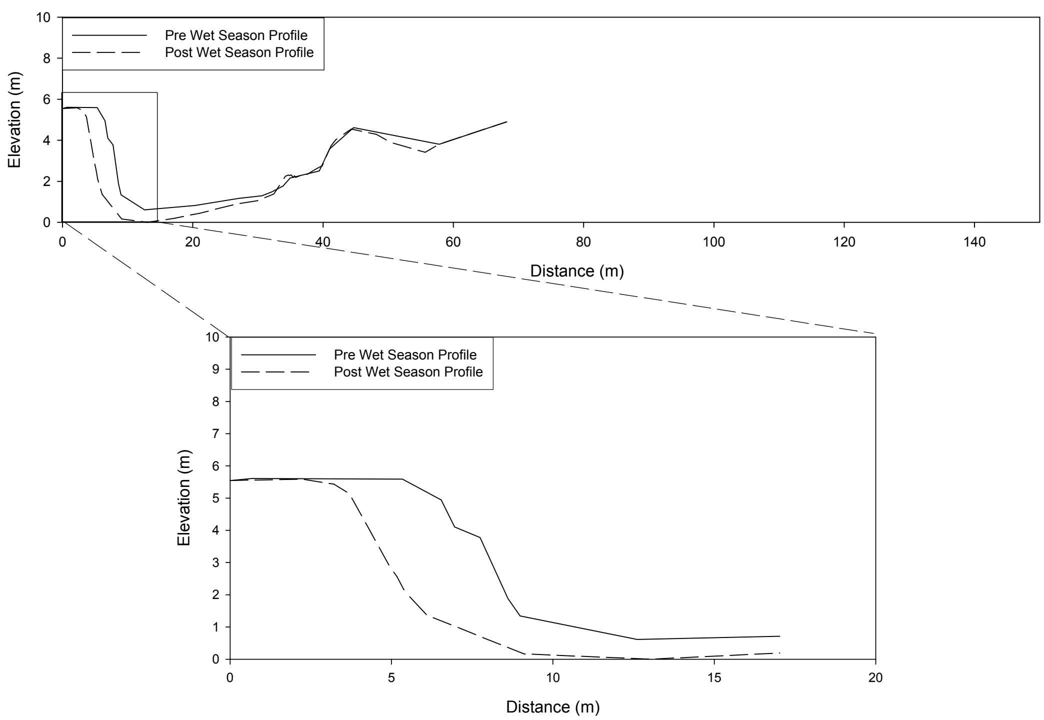
Appendix A.3 – JA0003 pre- and post-wet season channel and bank profiles.



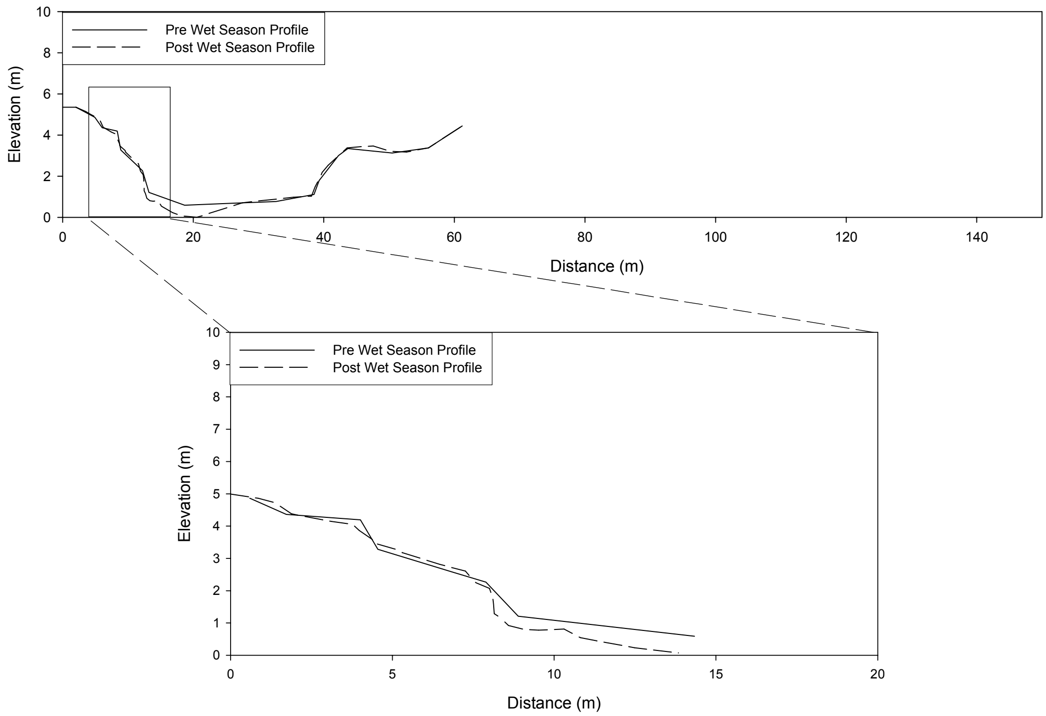
Appendix A.4 – JA0004 pre- and post-wet season channel and bank profiles.



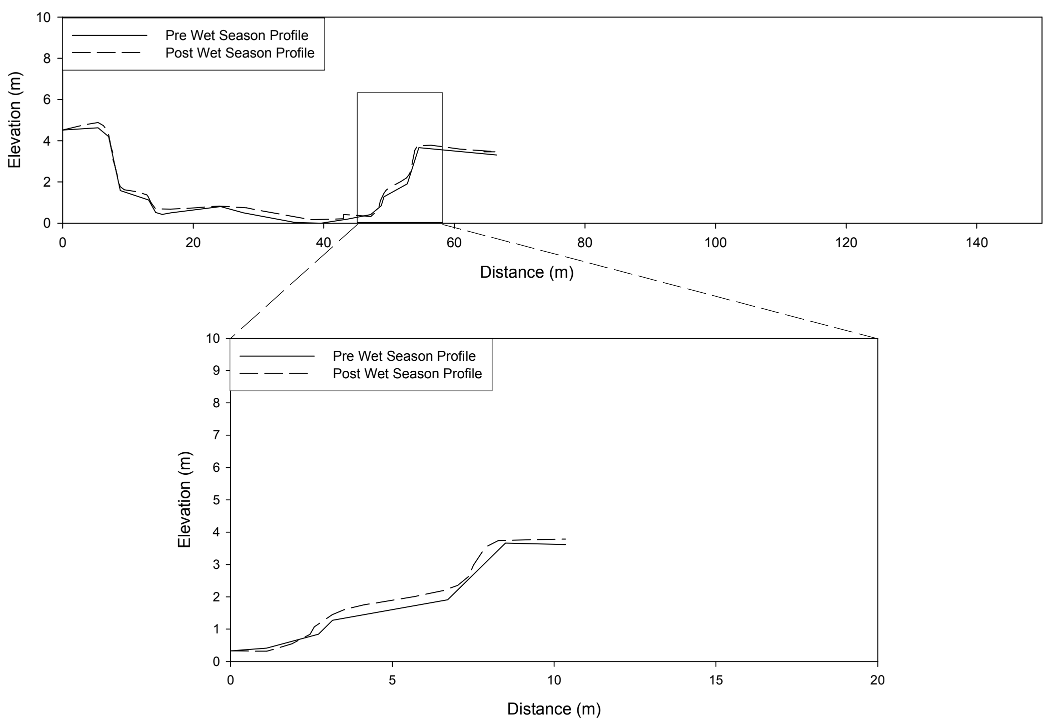
Appendix A.5 – JA0005 pre- and post-wet season channel and bank profiles.



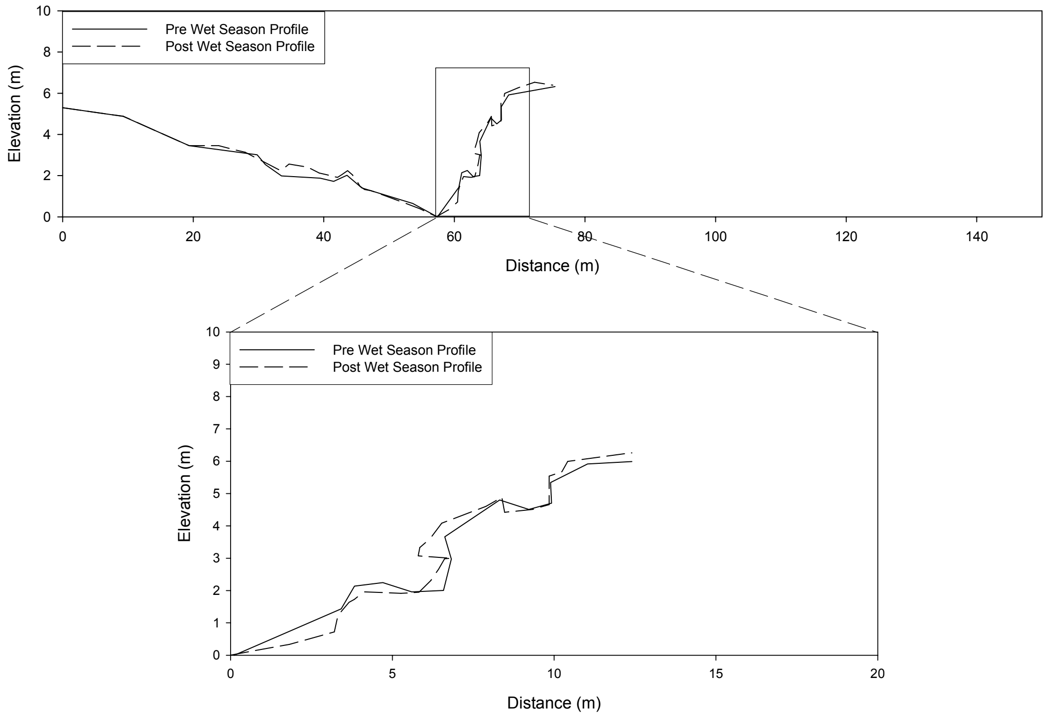
Appendix A.6 – JA0006 pre- and post-wet season channel and bank profiles.



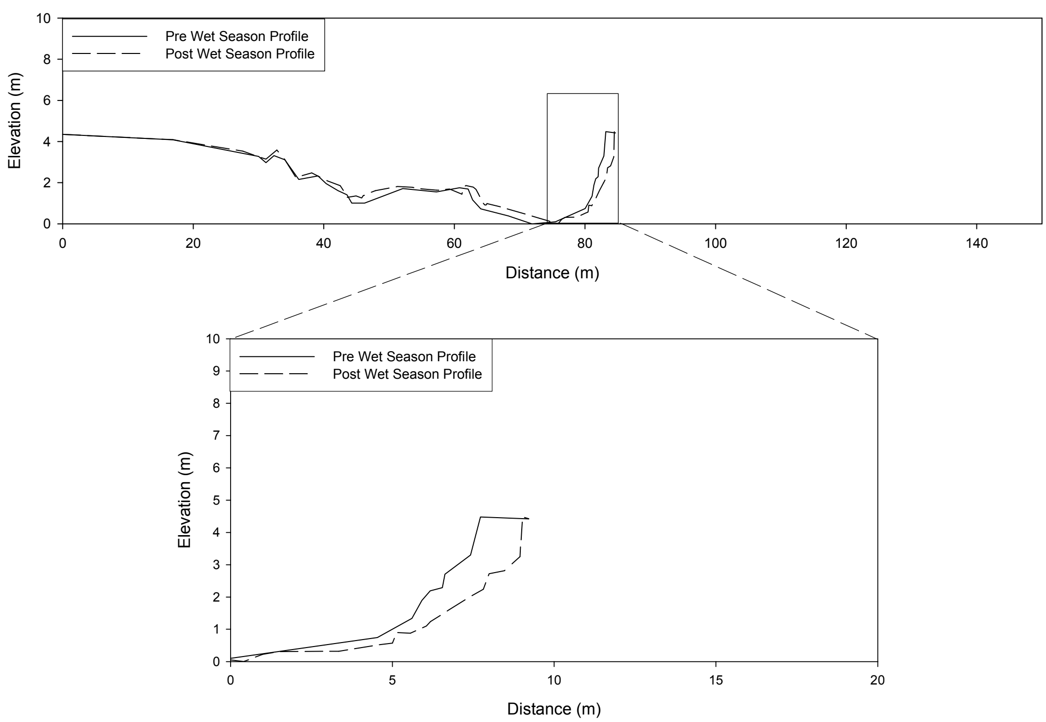
Appendix A.7 – JA0007 pre- and post-wet season channel and bank profiles.



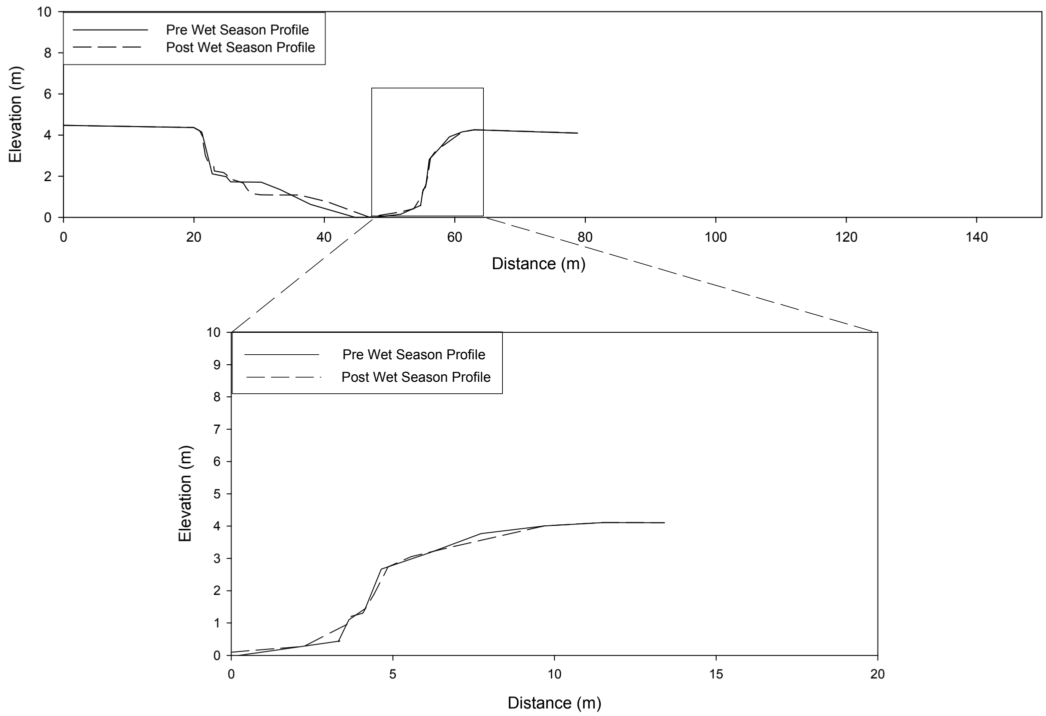
Appendix A.8 – JA0008 pre- and post-wet season channel and bank profiles.



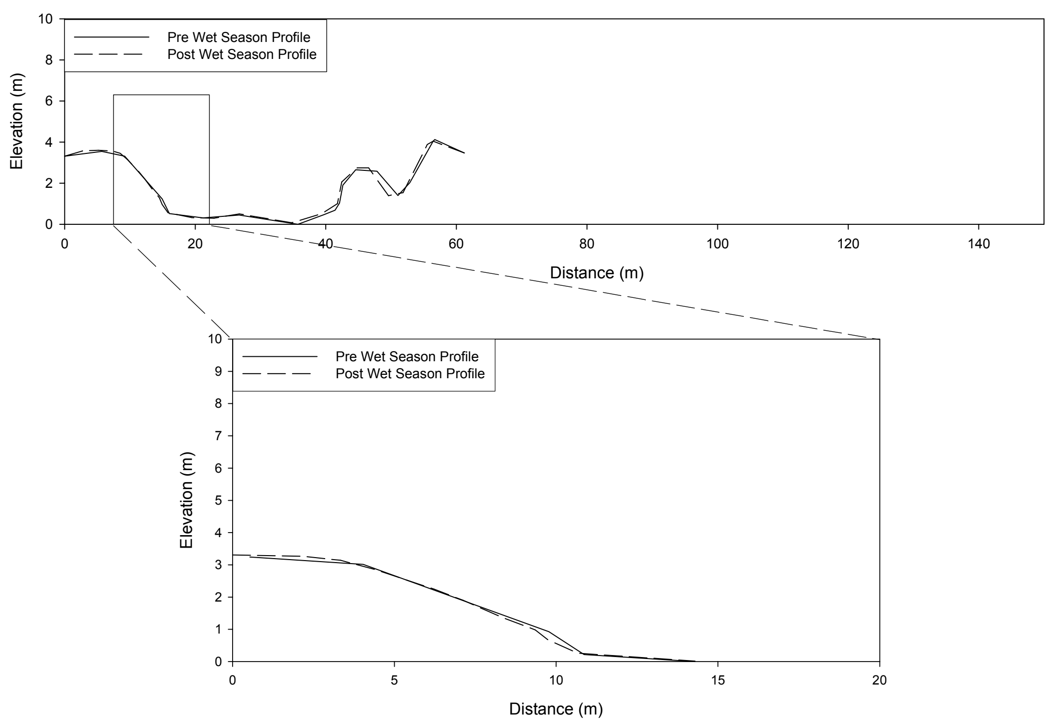
Appendix A.9 – JA0009 pre- and post-wet season channel and bank profiles.



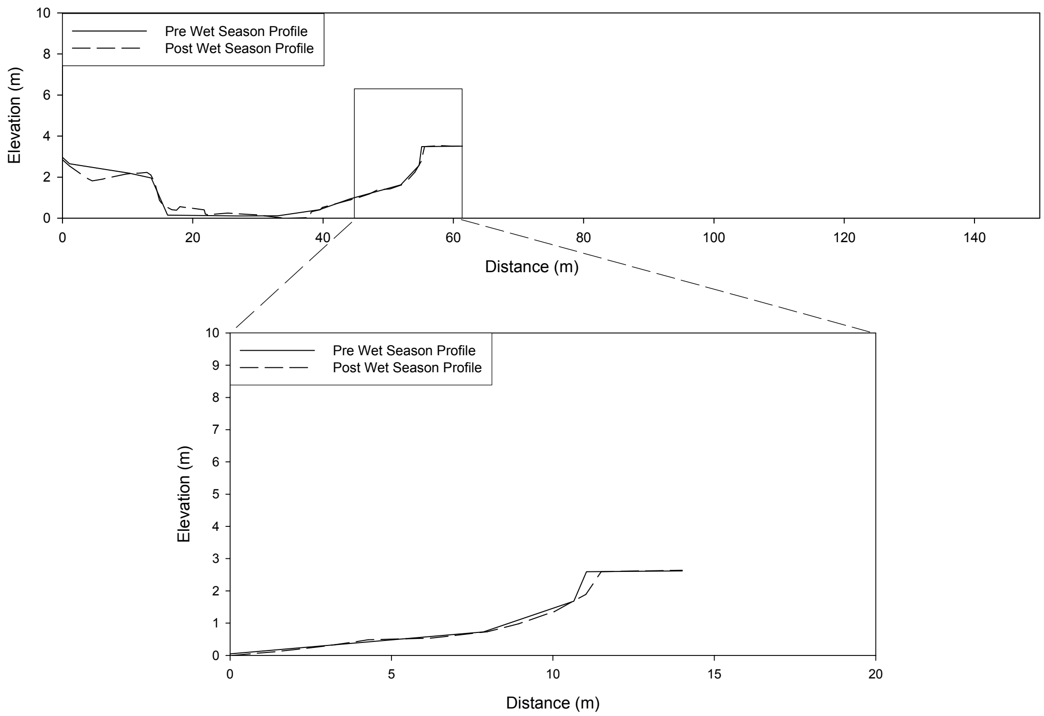
Appendix A.10 – JA0010 pre- and post-wet season channel and bank profiles.



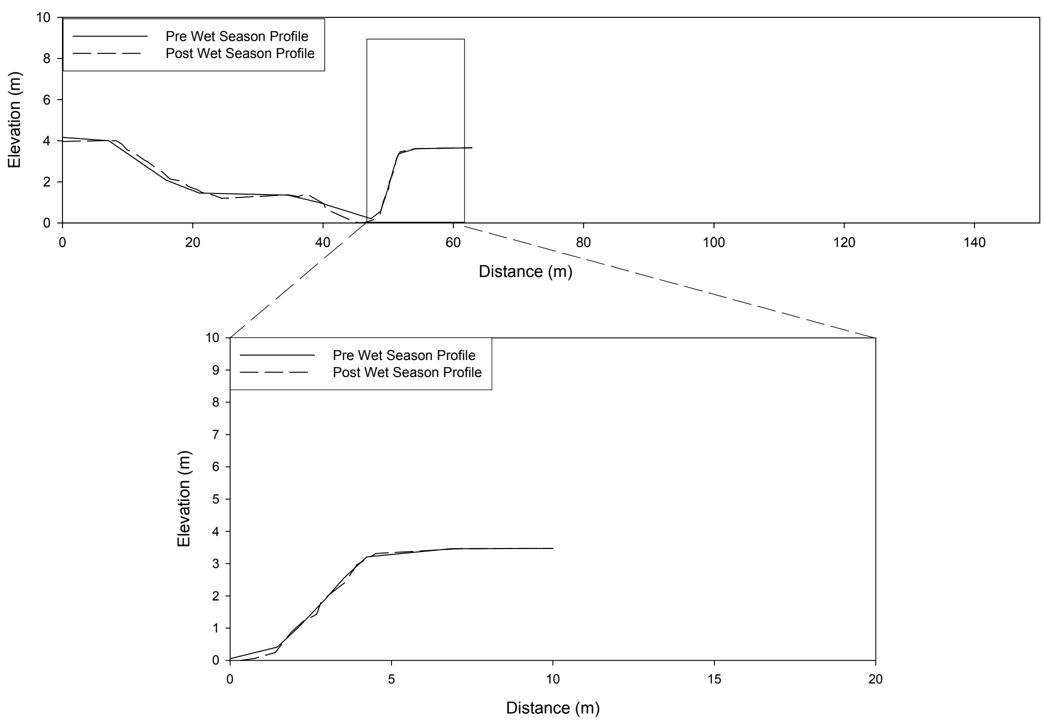
Appendix A.11 – LI0001 pre- and post-wet season channel and bank profiles.



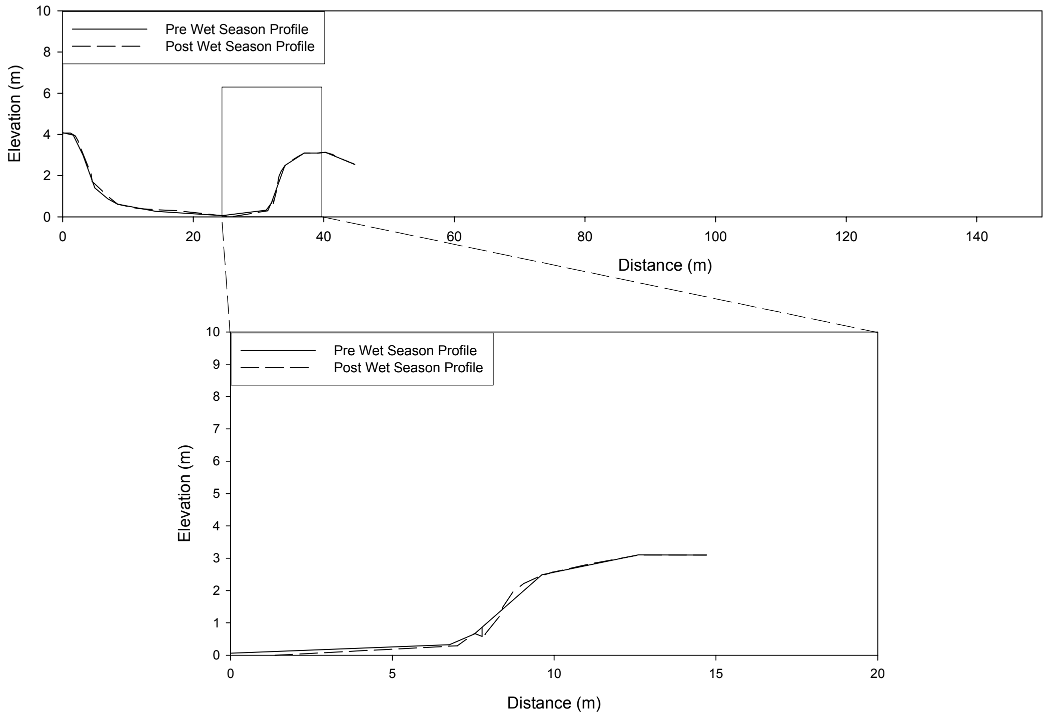
Appendix A.12 – LI0002 pre- and post-wet season channel and bank profiles.



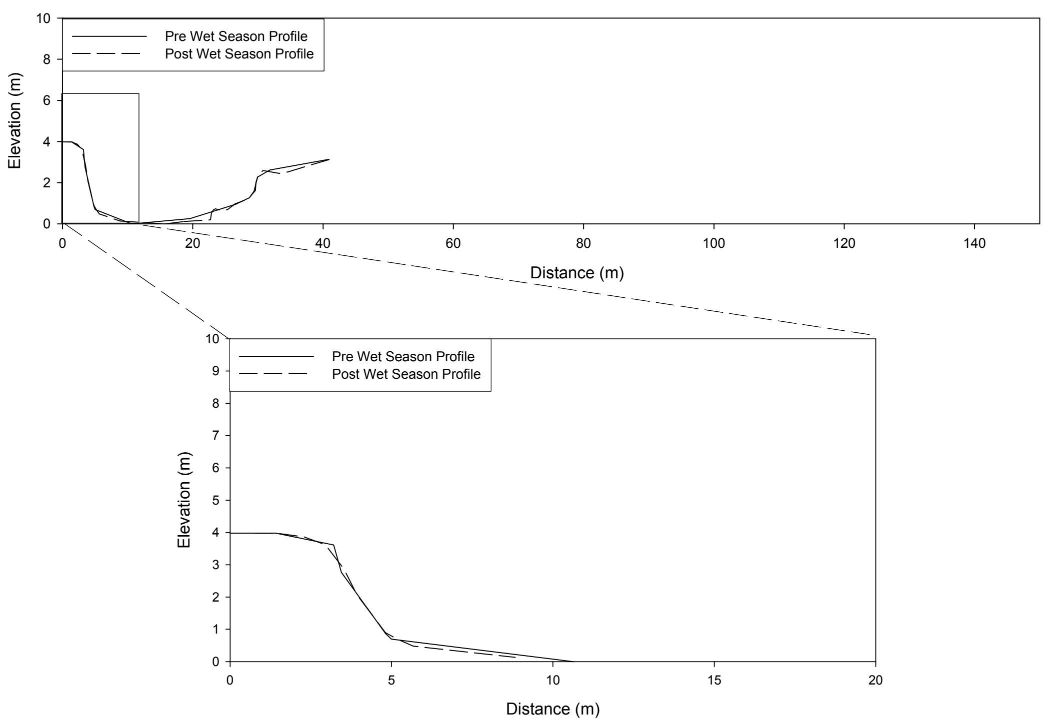
Appendix A.13 – LI0003 pre- and post-wet season channel and bank profiles.



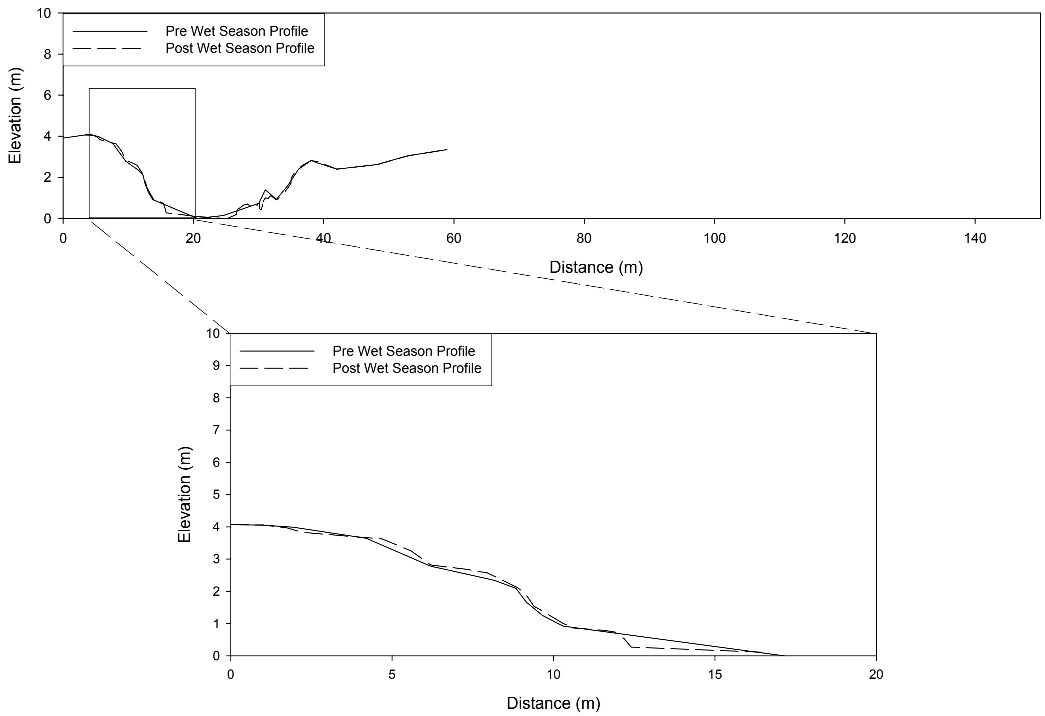
Appendix A.14 – LI0004 pre- and post-wet season channel and bank profiles.



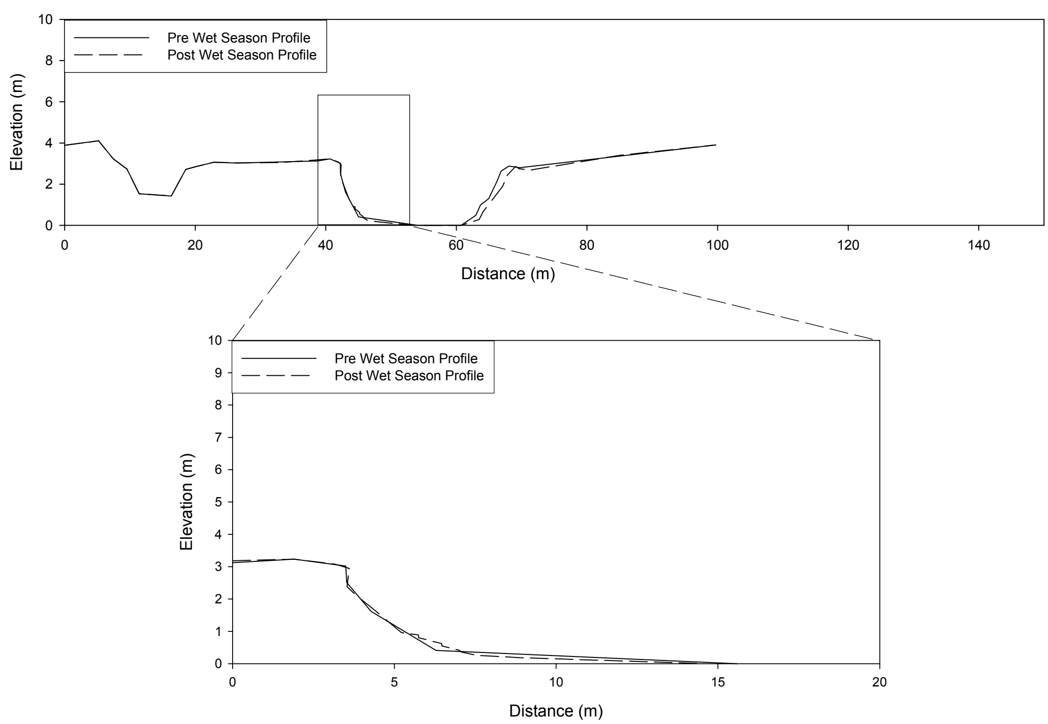
Appendix A.15 – LI0005 pre- and post-wet season channel and bank profiles.



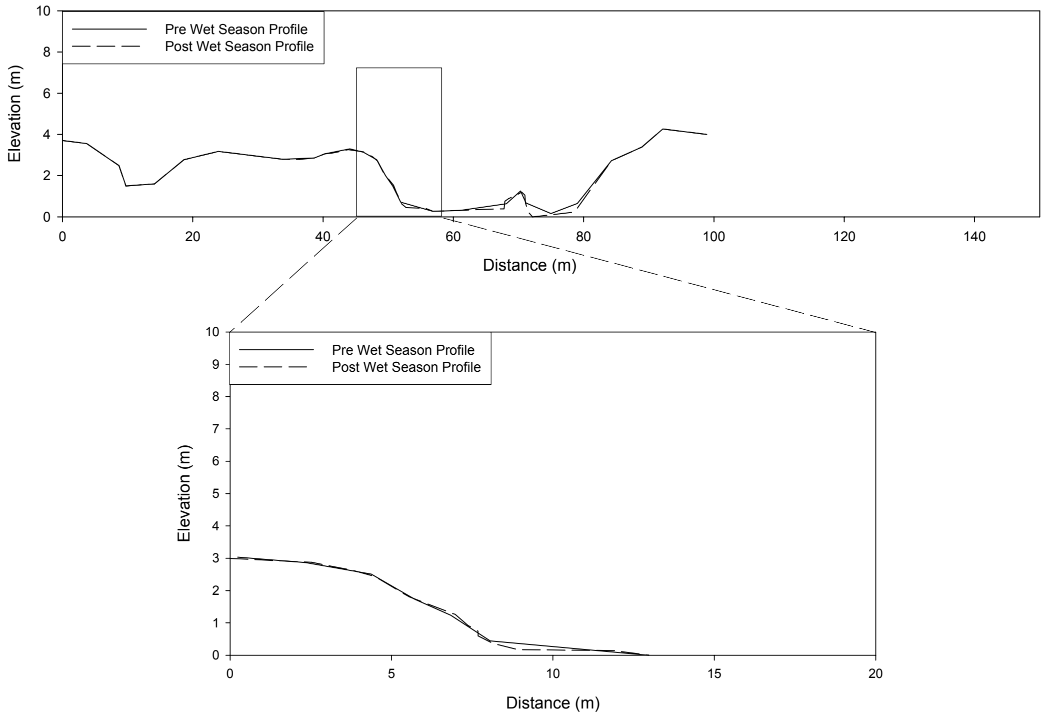
Appendix A.16 – LI0006 pre- and post-wet season channel and bank profiles.



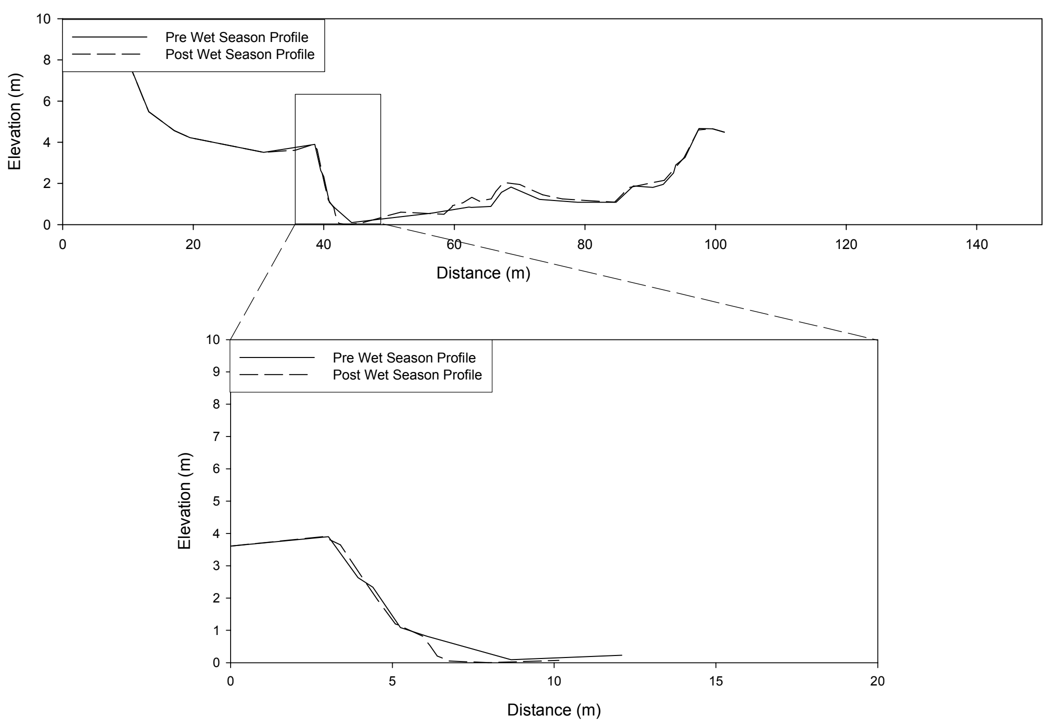
Appendix A.17 – LI0007 pre- and post-wet season channel and bank profiles.



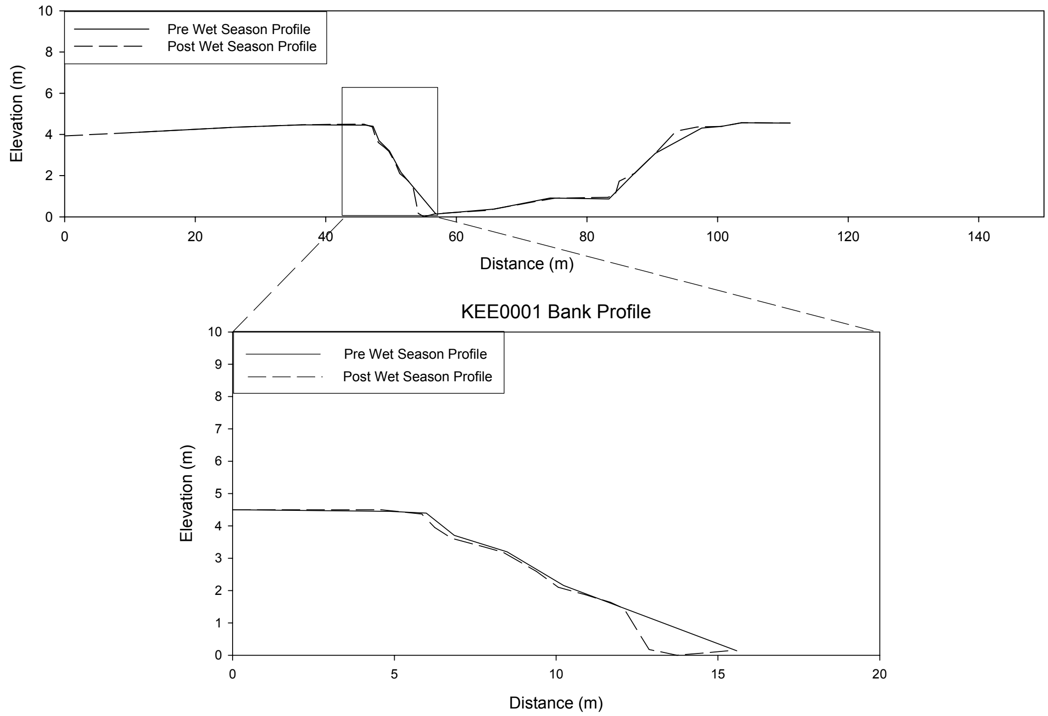
Appendix A.18 – LI0008 pre- and post-wet season channel and bank profiles.



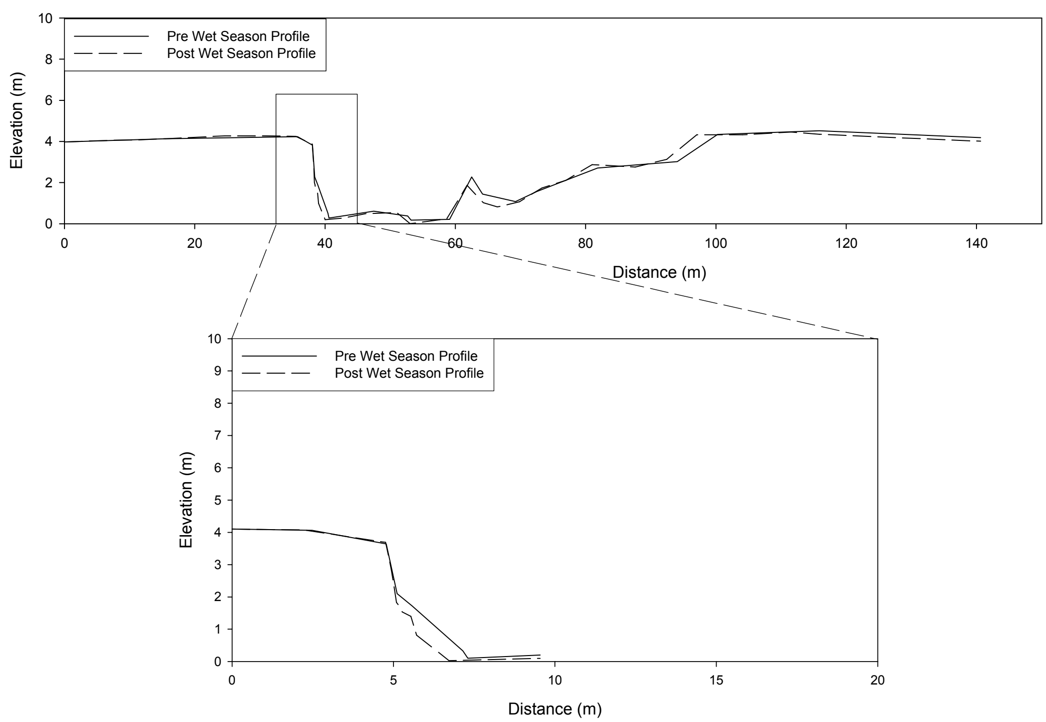
Appendix A.19 – LI0009 pre- and post-wet season channel and bank profiles.



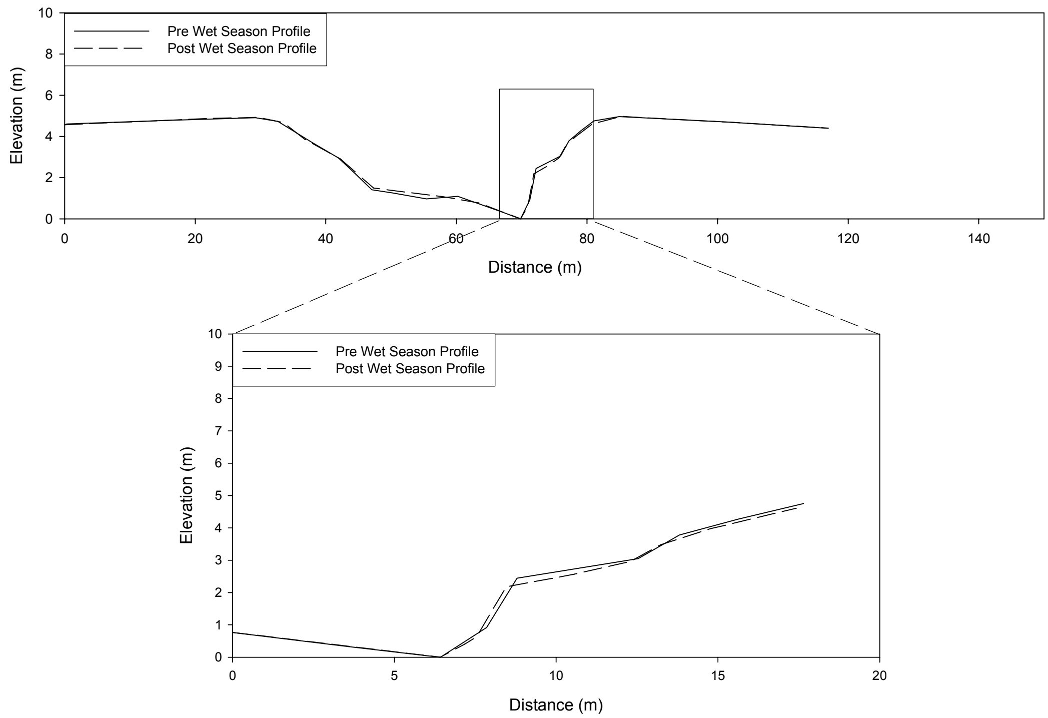
Appendix A.20 – LI0010 pre- and post-wet season channel and bank profiles.



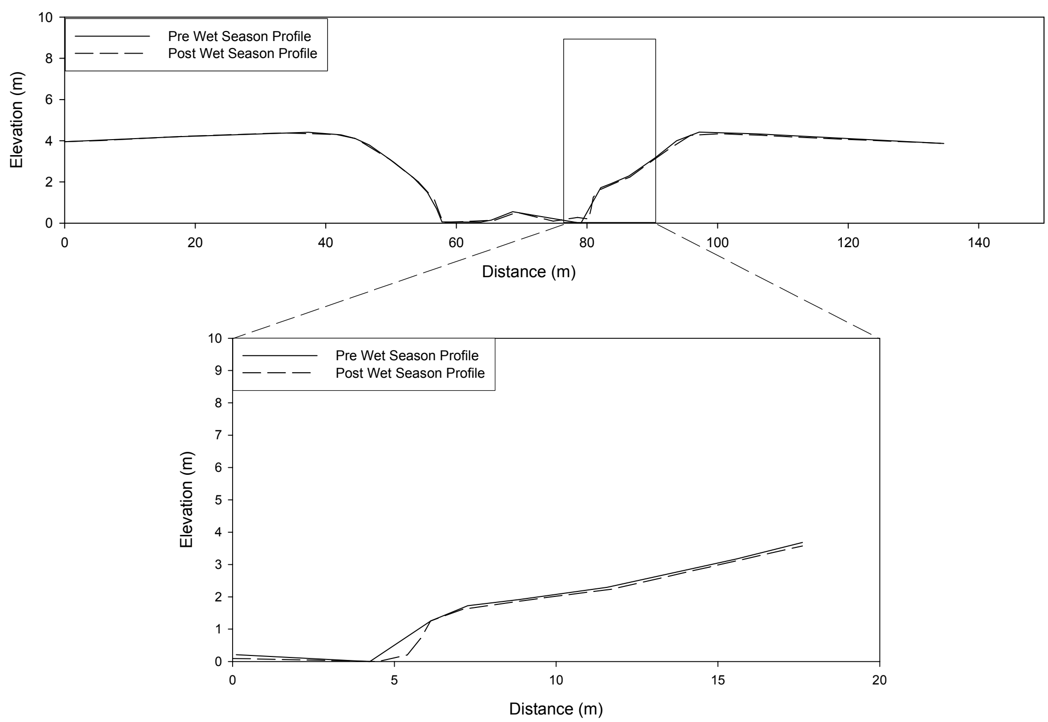
Appendix A.21 – TH0001 pre- and post-wet season channel and bank profiles.



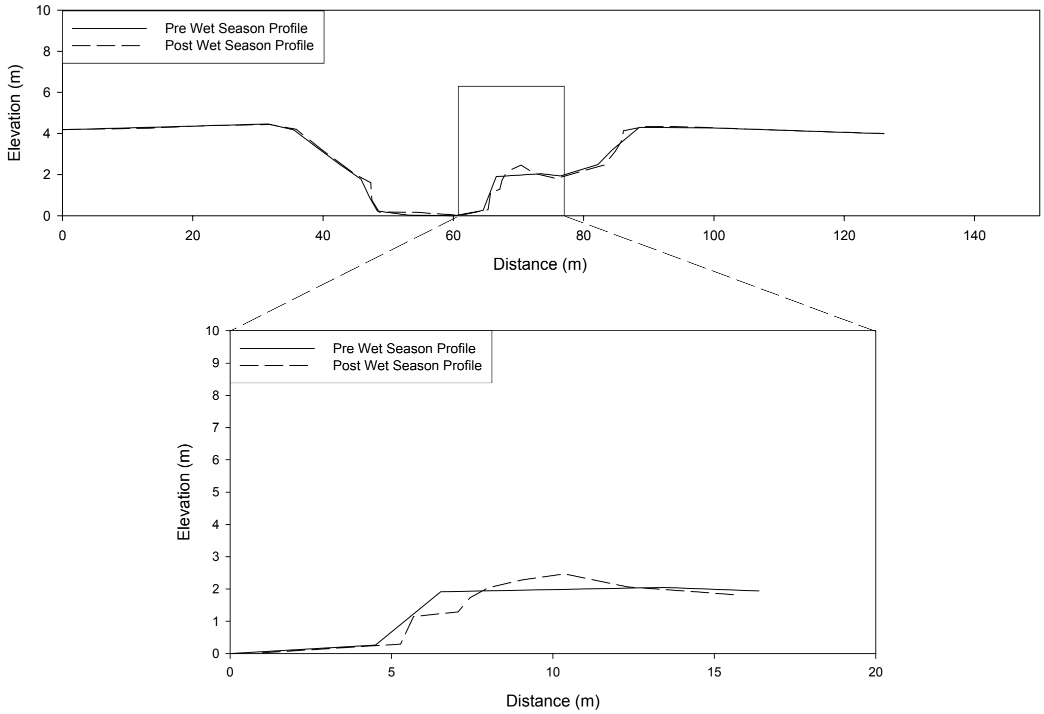
Appendix A.22 – TH0002 pre- and post-wet season channel and bank profiles.



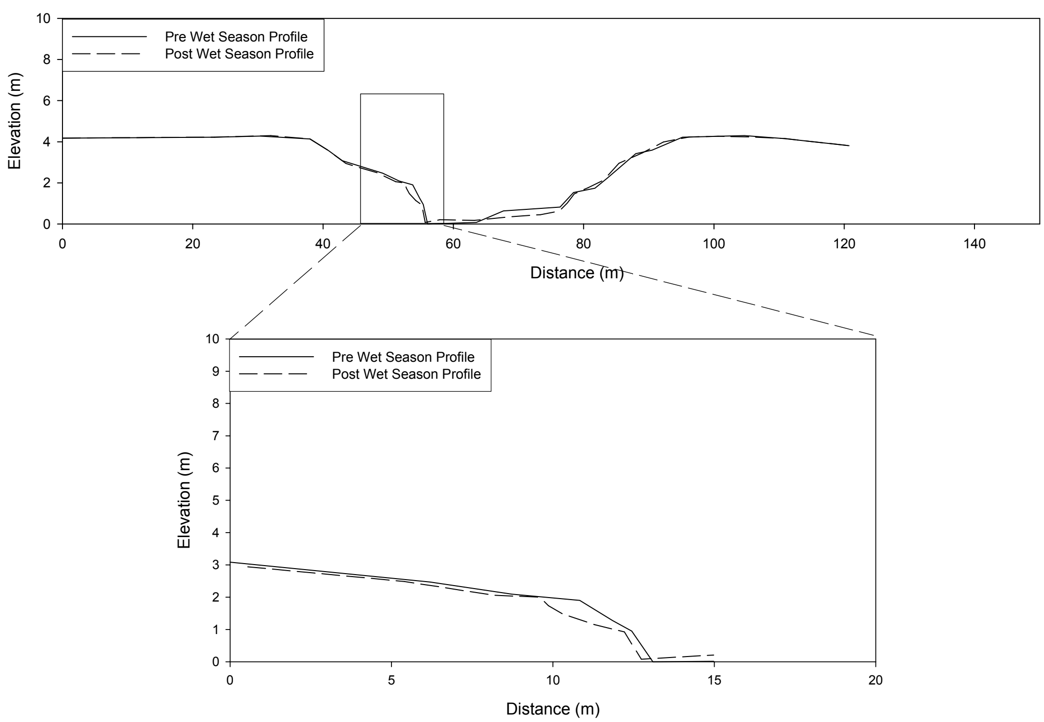
Appendix A.23 – TH0003 pre- and post-wet season channel and bank profiles.



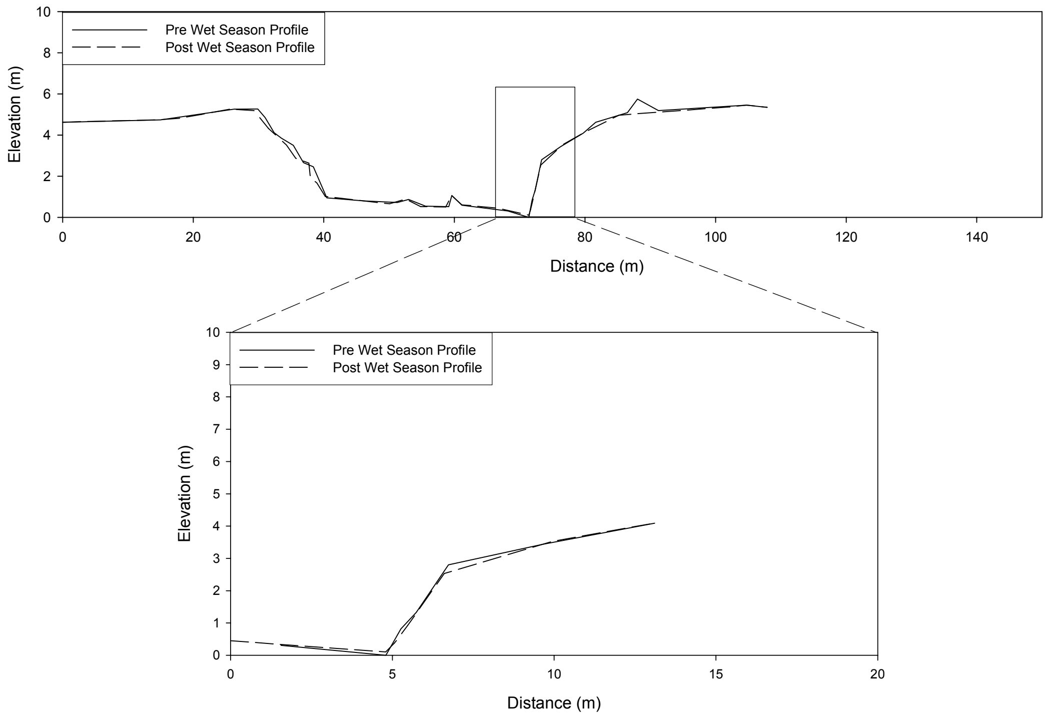
Appendix A.24 – TH0004 pre- and post-wet season channel and bank profiles.



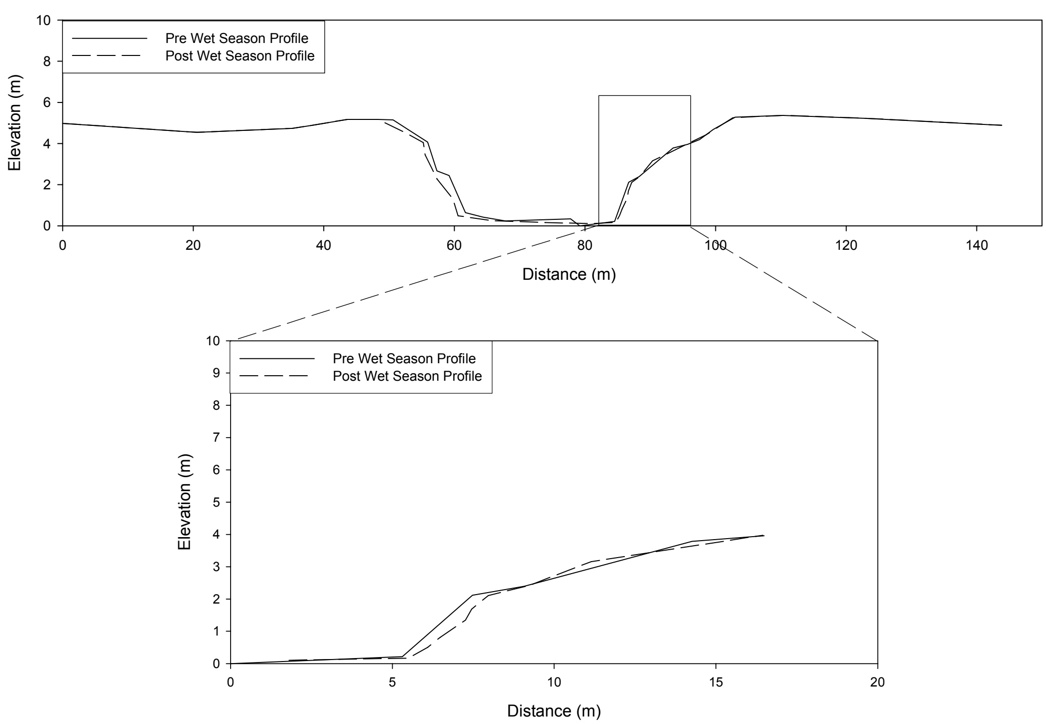
Appendix A.25 – TH0005 pre- and post-wet season channel and bank profiles.



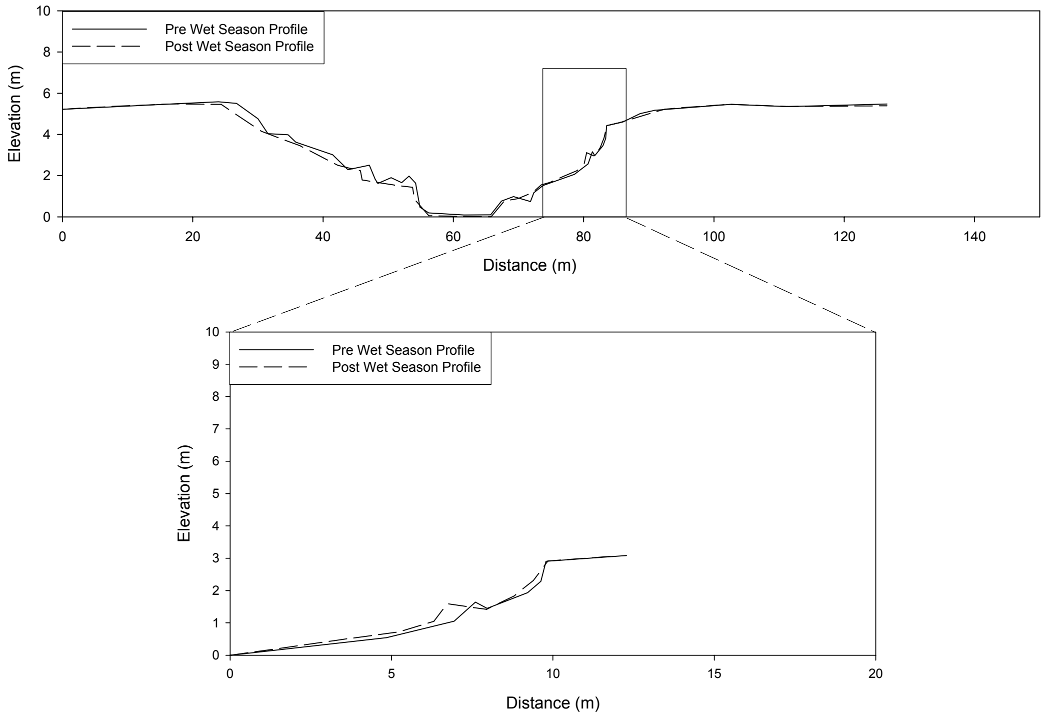
Appendix A.26 – TH0006 pre- and post-wet season channel and bank profiles.



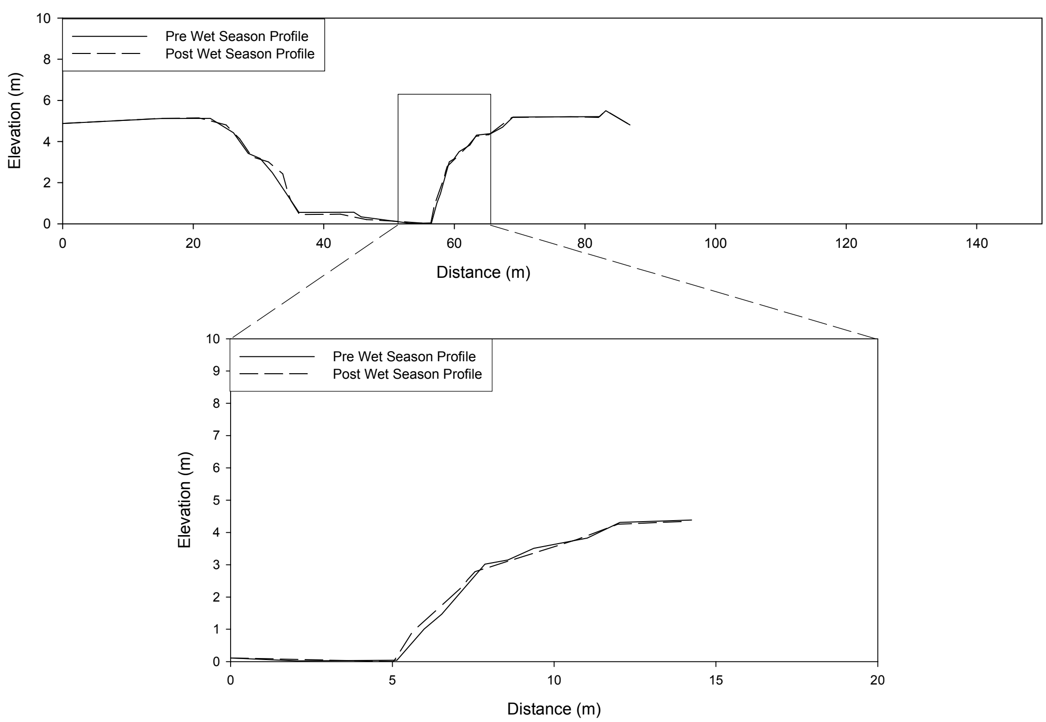
Appendix A.27 – TH0007 pre- and post-wet season channel and bank profiles.



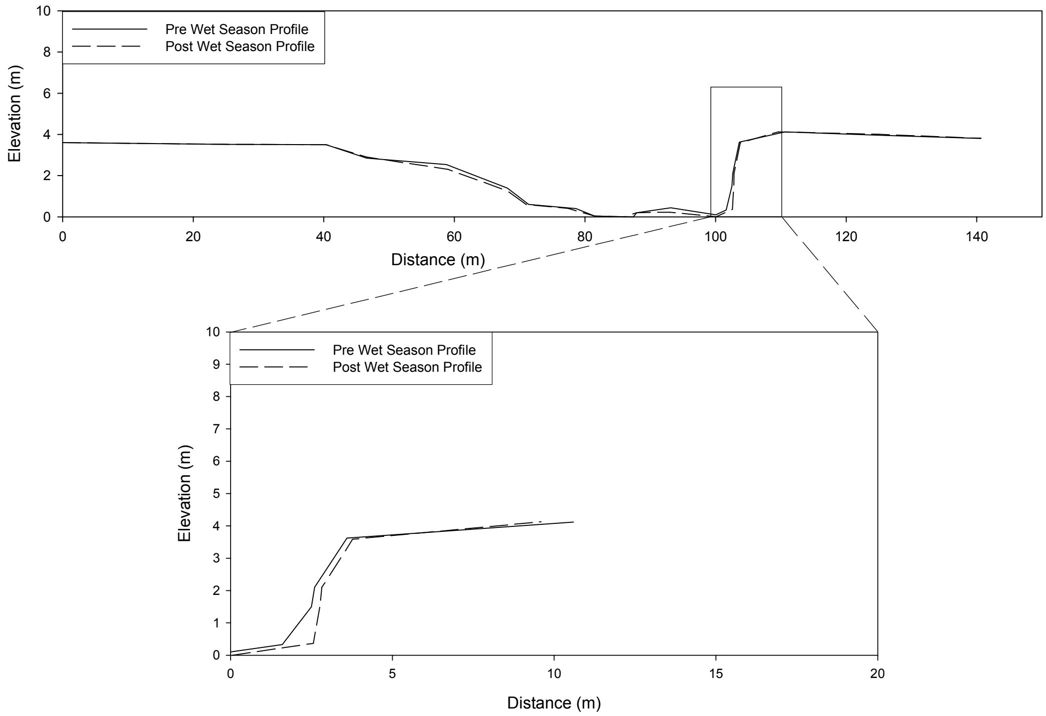
Appendix A.28 – TH0008 pre- and post-wet season channel and bank profiles.



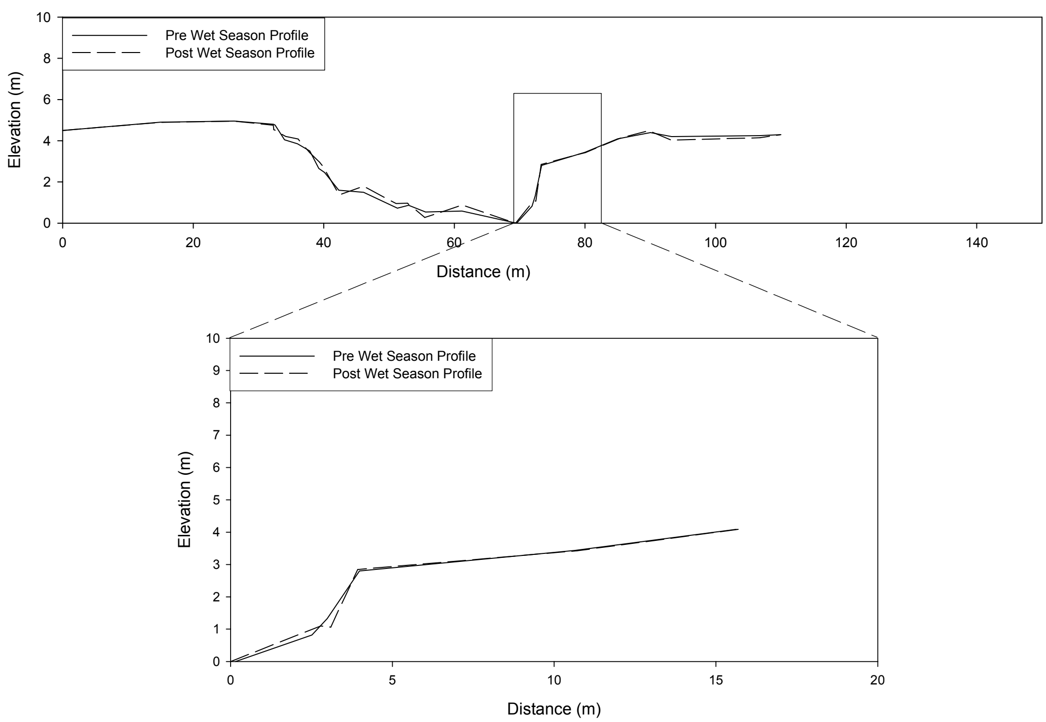
Appendix A.29 – TH0009 pre- and post-wet season channel and bank profiles.



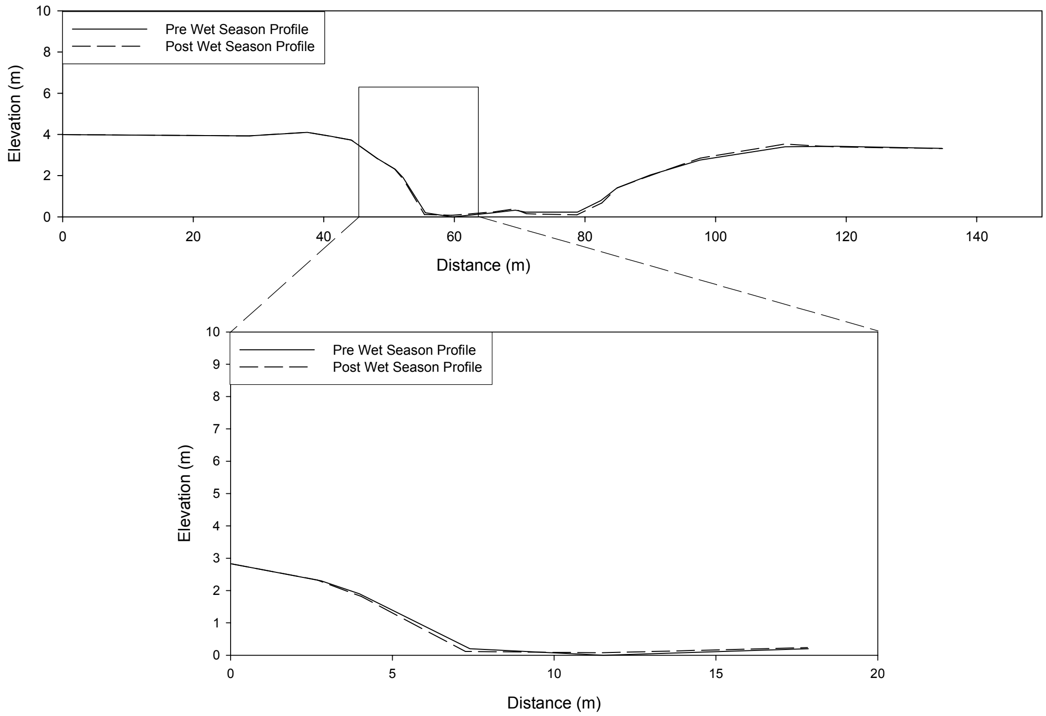
Appendix A.30 – TH0010 pre- and post-wet season channel and bank profiles.



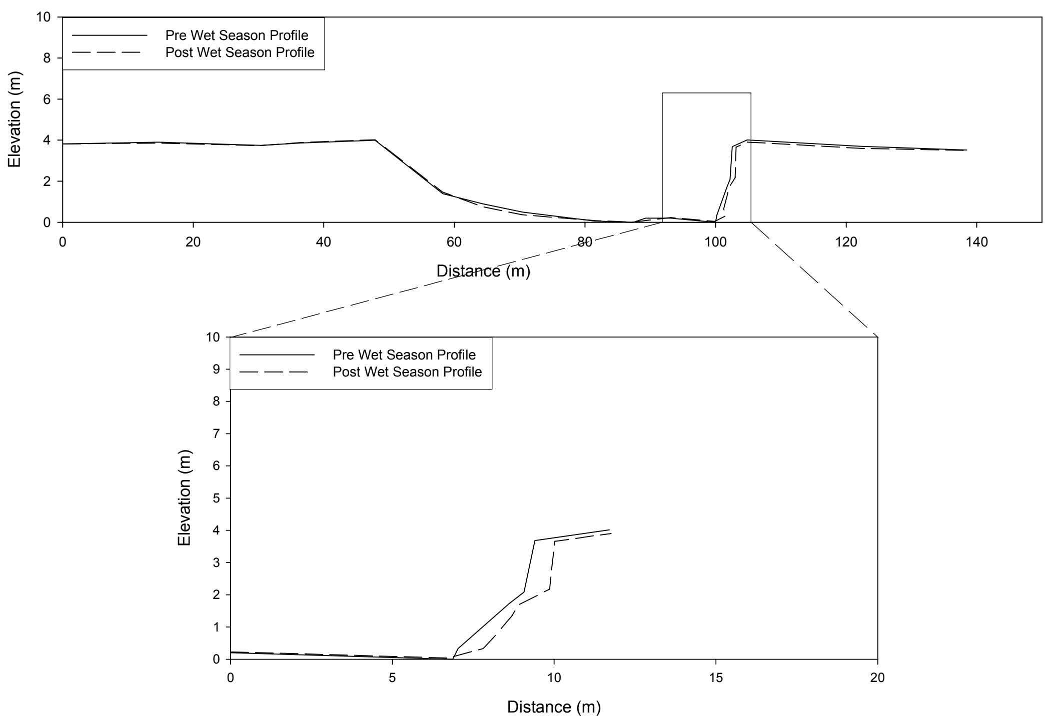
Appendix A.31 – TH0011 pre- and post-wet season channel and bank profiles.



Appendix A.32 – TH0012 pre- and post-wet season channel and bank profiles.



Appendix A.33 – TH0013 pre- and post-wet season channel and bank profiles.



Appendix A.34 – TH0014 pre- and post-wet season channel and bank profiles.

APPENDIX B

Appendix B.1 – JA0001 bank, with failed debris collected at toe.

Appendix B.2 – JA0002 bank, with failed debris collected at toe.

Appendix B.3 – JA0003 bank, with failed debris collected at toe.

Appendix B.4 – Upstream from JA0003 showing outer bank cantilever failure on a treeless section of bank.

Appendix B.5 – JA0004 bank, showing failed upper section.

Appendix B.6 – JA0005 bank, showing stabled treed section.

Appendix B.7 – JA0006 bank, showing failed vegetated bank.

Appendix B.8 – JA0007 bank, showing toe scour and associated undercutting of the upper bank.

A B

Appendix B.9 – Site JA0008, showing (A) vegetated channel reach; and (B) stable vegetated bank

Appendix B.10 – JA0009 bank, showing toe scour and undercutting of upper bank.

A B

Appendix B.11 – Site JA0010, showing (A) slumped material collected at the base of the bank; and (B) cantilever failure of the un-treed sections of the bank.

Appendix B.12 – Site LI0001, showing stable un-treed bank.

Appendix B.13 – Site LI0002, showing vegetated stable bank.

Appendix B.14 – LI0003 bank, showing toe scour and undercutting of the upper bank.

Appendix B.15 – Site LI0004, showing well vegetated stable bank.

Appendix B.16 – Site LI0005, showing well vegetated banks.

A

B

Appendix B.17 – Site LI0006, showing (A) well vegetated bank; and (B) toe scour and undercut.

A

B

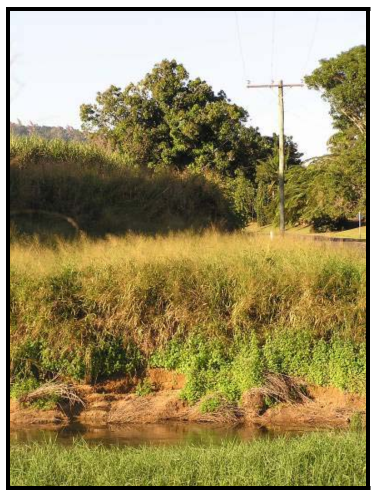
Appendix B.18 – Site LI0007, showing (A) pre-flood condition; and (B) post-flood basal scour and vegetation removal.

A

B

Appendix B.19 – Site LI0008, showing (A) upstream photo of well vegetated banks; and (B) stable, well vegetated left bank.

Appendix B.20 – Site LI0009, showing root armouring of the lower bank.



Appendix B.21 – LI0010 bank showing pre-flood failed basal blocks. These were eroded away during the 2003/2004 wet season.

A **B**

Appendix B.22 – Site TH0001, showing (A) entire bank; and (B) basal scour.

Appendix B.23 – Site TH0002, showing scour of the middle sandy strata.

Appendix B.24 – Site TH0003, showing dry channel bed and stable, un-treed banks.

Appendix B.25 – TH0004 bank, showing sediment sampling of lower strata.

Appendix B.26 – TH0005 bank, showing sediment sampling of upper strata.

Appendix B.27 – Site TH0006.

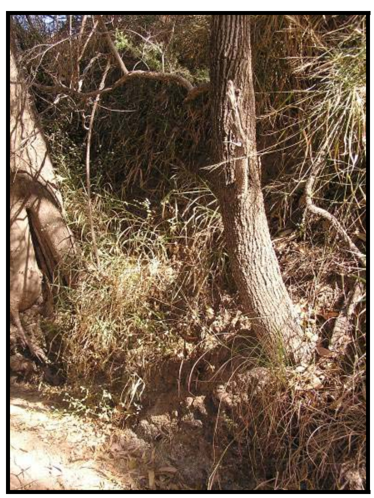
Appendix B.28 – TH0007 bank, showing steep, stable section.

Appendix B.29 – TH0008 bank.

Appendix B.30 – Site TH0009, showing pre-wet season slumping upstream of site.

Appendix B.31 – TH0010 bank, showing a stable site with a low density of trees.

Appendix B.32 – Site TH0011, showing scour of middle sandy strata and associated undercutting of the upper clayey strata.



Appendix B.33 – TH0012 bank, showing stable vegetated bank.

Appendix B.34 – TH0013 bank, showing well vegetated, stable bank.

Appendix B.35 – Site TH0014, showing the three different bank strata.