supervising scientist report **176**

Bank erosion in the Ngarradj catchment: Results of erosion pin measurements between 1998 and 2001

MJ Saynor, WD Erskine
& KG Evans

Australian Government
Department of the Environment and Heritage
Supervising Scientist

Mike Saynor – Environmental Research Institute of the Supervising Scientist,
GPO Box 461, Darwin NT 0801, Australia.

Wayne Erskine – Office of the Supervising Scientist, GPO Box 461,
Darwin NT 0801, Australia. (Current address: Environmental Management and Forest Practices Directorate, State Forests of NSW, PO Box 100, Beecroft NSW 2119)

Ken Evans – Environmental Research Institute of the Supervising Scientist,
GPO Box 461, Darwin NT 0801, Australia.

This report should be cited as follows:

MJ Saynor, WD Erskine & KG Evans 2003. *Bank erosion in the Ngarradj catchment: Results of erosion pin measurements between 1998 and 2001*. Supervising Scientist Report 176, Supervising Scientist, Darwin NT.

The Supervising Scientist is part of the Australian Government Department of the Environment and Heritage.

Supervising Scientist
Department of the Environment and Heritage
GPO Box 461, Darwin NT 0801 Australia

ISSN 1325-1554

ISBN 0 642 24384 0

Printed and bound in Darwin by NTUniprint, Darwin

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Executive summary

A sediment budget has been adopted to assess the physical impacts, if any, of the Jabiluka uranium mine on the Ngarradj catchment in the seasonally wet tropics of northern Australia. Permanently marked cross sections are used to measure large-scale bank erosion and sediment storage, and erosion pins are used to measure slower rates of bank retreat (Erskine et al 2001). A total of 193 erosion pins were installed at 49 sites in seven formally defined channel reaches on four streams in the Ngarradj catchment and were measured at the end of both the wet and dry seasons for up to three years between 1998 and 2001. The four streams were Tributary North and Tributary Central, which drain the Jabiluka mine site, and Ngarradj and East Tributary. The seven channel reaches of Erskine et al (2001) that were investigated included:

- The Gullied Reach on lower Tributary North;
- The Sinuous Reach, Large Capacity Reach and Small Capacity Reach on lower Tributary Central;
- The Forested Meandering Reach (upper Swift Creek or upmain gauge – UM) and Sinuous Reach (Swift Creek gauge – SC) on Ngarradj; and
- The Forested Meandering Reach on East Tributary (East Tributary gauge – ET).

The bank erosion measurements occurred during a period of above average rainfall and streamflow (1998–2001) and established that:

- Substantial bank erosion occurred during the wet season on the mine site tributaries by rapid lateral migration (Tributary Central) and by erosion of gully sidewalls by a combination of within-gully flows and overland flow plunging over the sidewalls (Tributary North);
- Bank erosion also occurred during the dry season by desiccation and loss of cohesion of the sandy sediments, by faunal activity and by dry flow processes;
- Channels with dense riparian vegetation (forested meandering reaches) did not generate significant amounts of sediment by bank erosion;
- Deposition (ie negative pin values were commonly recorded) was also locally significant, despite the sandy bank sediments. This indicates that bank erosion is an episodic process that is not characterised by quasi-continuous bank retreat; and
- Bank profile form and channel planform exert a strong control on erosion rates during the wet but not during the dry season.

Bed scour was greater at the gauging stations than in the mine site tributaries over the same time period that the erosion pin measurements were made (Saynor et al 2002b). Therefore, bed scour and consequent bank undermining were not significant causes of bank erosion in the Ngarradj catchment.

The present erosion pin program exhibited a number of minor shortcomings that should be redressed in future. It is recommended that:

- The erosion pin program in the Ngarradj catchment should be reduced by concentrating solely on the mine site tributaries.
- The erosion pin program should cease at the upper Swift Creek and East Tributary gauging station sites due to the stable channel boundary. The forested banks and high large woody debris loading contribute to this stability.

- Pins are not effective at the Swift Creek gauging station because of the sandy, gently sloping banks. The current program should be terminated.
- Pins are not needed at the cross sections on Tributary Central where rapid lateral migration is currently occurring and permanently marked cross sections have been installed (TC06, TC07, TC11).
- A recovery peg and/or base line should be installed at the top of the bank to aid in pin recovery.
- Stainless steel pins should be used to stop rusting. Rusted pins cause the binding of sediment to the pin and cause problems with pin measurement.
- Pins should never be replaced when they have been buried.
- Erosion pin sample sites should representatively cover the full range of channel planforms and bank types to enable meaningful spatial extrapolation of the results.
- The reduced but improved erosion pin program should be implemented to target the most active bank erosion sites and to enable a more cost-effective and management-focussed program to be maintained.

Acknowledgments

Ann Webb assisted greatly with the production, editing and finalisation of the report. The constructive referees comments of Dr Greg Hancock and Dr Ashley Webb on an earlier version of the report are gratefully acknowledged. We thank Bryan Smith, Gary Fox and Elice Crisp for their diligent field work and Dene Moliere for assistance with the hydrology. ERA kindly allowed access to the Jabiluka Mineral Lease to conduct the field measurements. Dr Max Finlayson constructively reviewed the final report.

Bank erosion in the Ngarradj catchment: Results of erosion pin measurements between 1998 and 2001

MJ Saynor, WD Erskine & KG Evans

1 Introduction

Following the refusal of the traditional landowners to permit the trucking of uranium ore from Energy Resources of Australia's (ERA) Jabiluka mine to its other nearby mine at Ranger, the Jabiluka Mill Alternative was developed. This alternative involved the construction of a new mill at Jabiluka and was outlined in a Public Environment Report (Kinhill & Energy Resources of Australia Ltd 1998). The Commonwealth Government approved the on-site mill proposal in August 1998, subject to a number of environmental requirements (Johnston & Prendergast 1999). Work on the mine began immediately after government approval but has since changed to a 'care and maintenance phase' without the processing of any ore. The Jabiluka Mining Lease (JML) is surrounded on three sides by Kakadu National Park and by the Ranger Mining Lease on the fourth (fig 1).

Erskine et al (2001) proposed that a sediment budget should be adopted to assess the physical impacts, if any, of the Jabiluka uranium mine on the Ngarradj[1] catchment in the seasonally wet tropics of northern Australia (fig 1). This sediment budget requires measurements of suspended sediment and bed load fluxes at gauging stations as well as soil erosion and storage rates on similar landforms throughout the catchment and channel scour and fill, channel erosion rates and in-channel sediment storage at representative sites within homogeneous river reaches located throughout the channel network (Reid & Dunne 1996).

Ngarradj is a major downstream right bank tributary of Magela Creek, which flows directly into the Magela Creek floodplain. The Magela Creek and floodplain are listed as Wetlands of International Importance under the Ramsar Convention and recognised under the World Heritage Convention.

Initial field inspections of the Ngarradj catchment were conducted during the 1998 dry season to identify reaches in which channel erosion rates could be measured as part of a sediment budget to determine the possible effects of the Jabiluka mine on sediment generation, storage and transport rates (Saynor 2000, Erskine et al 2001). Erskine et al (2001) recommended that thirteen projects should be undertaken to determine the physical impacts of uranium mining on Ngarradj, with one being selective measurement of bank erosion and nickpoint migration rates. Most projects were initiated between August and December 1998.

The mine site tributaries (Tributaries North and Central in fig 1) and Ngarradj were identified as requiring detailed investigation of channel erosion rates and sediment storage because they are the pathways for the movement of sediment from the Jabiluka mine to Magela Creek (Erskine et al 2001).

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[1] The name Ngarradj refers to a creek that drains the catchment in which Jabiluka Mine is located and that flows into the Magela Creek wetlands. Ngarradj has also been referred to in previous reports as Swift Creek. Ngarradj is the Aboriginal name for this creek system. The full term is Ngarradj Warde Djobkeng meaning the site where the cockatoo vomited on and split the rocks to form the creek known as Ngarradj. It is one of several dreaming (Djang) sites on or adjacent to the Jabiluka mine lease (A Ralph, Gundjehmi Aboriginal Corporation, 2001).

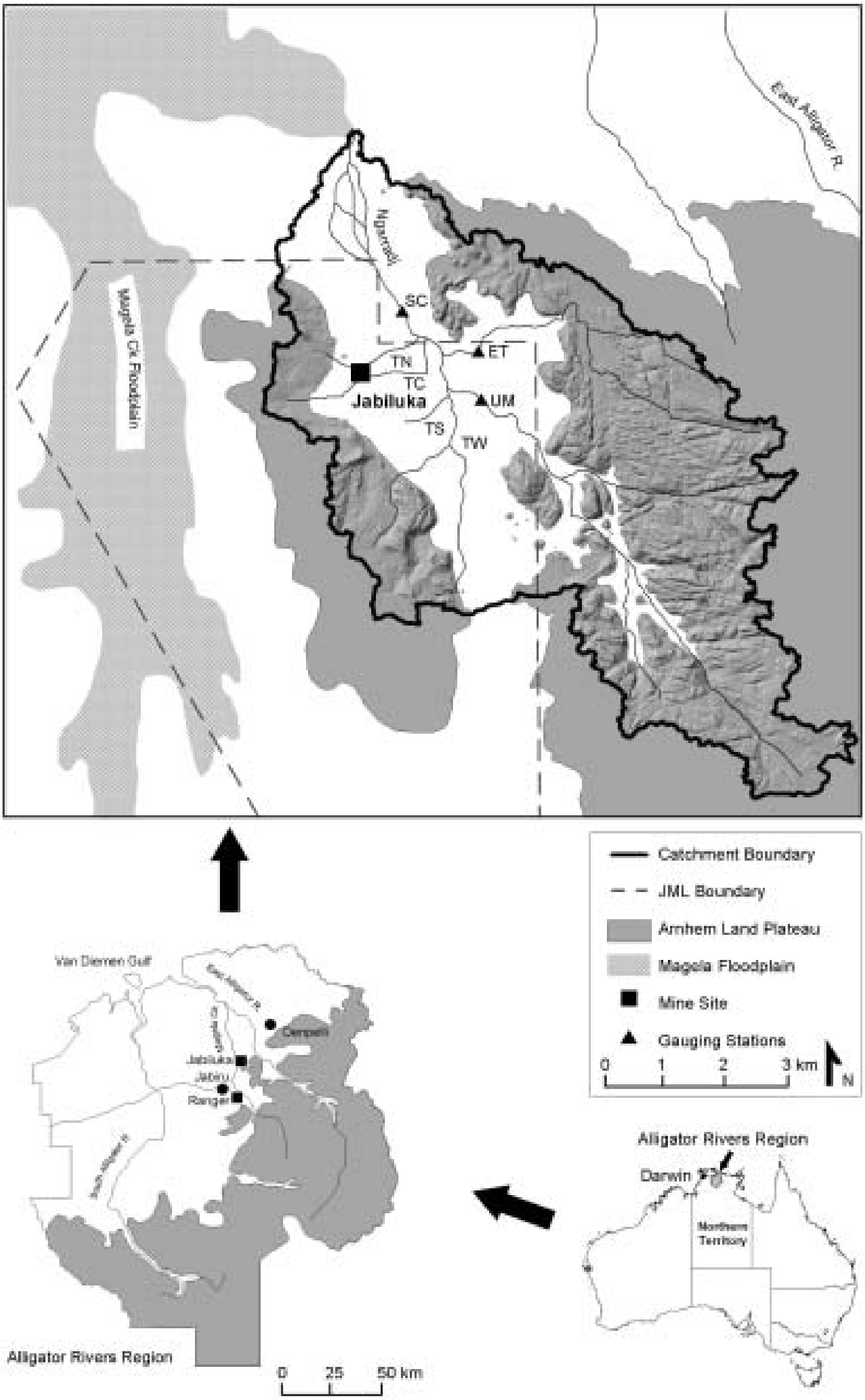

Figure 1 Location of the Ngarradj catchment in the Alligator Rivers Region of northern Australia. The ***eriss*** gauging stations are lower Swift Creek (SC), upper Swift Creek (UM) and East Tributary (ET). The additional abbreviations are Tributary North (TN), Tributary Central (TC), Tributary South (TS) and Tributary West (TW). JML refers to the Jabiluka Mining lease.

Permanently marked cross sections were recommended for measuring large-scale bank erosion and sediment storage only, and erosion pins were recommended to measure slower rates of bank retreat (Erskine et al 2001). The results of measurements of large-scale bank erosion by repeated cross-sectional surveys and of nickpoint erosion by repeated tacheometric surveys are documented in Saynor et al (2002a). Rainfall simulation was used to assess soil erosion rates of mine stockpiles and natural soils (Duffy 2001). The current report discusses the results of repeated measurements of erosion pins on the mine site tributaries and at the gauging stations in the Ngarradj catchment (fig 1). Results of wet season scour and fill of the channels in the Ngarradj catchment based on scour chains are outlined in Saynor et al (2002b). They found that mean scour ranged from a minimum of 50 ± 34 mm on Tributary North during the 1999/2000 wet season to a maximum of 332 ± 93 mm at Swift Creek during the 2000/2001 wet season. Mean fill ranged from a minimum of 56 ± 18 mm on Tributary North during the 2000/2001 wet season to a maximum of 391 ± 43 mm at Swift Creek during the 1998/1999 wet season. Average scour and fill during each wet season in each measurement reach overlapped with each other allowing for plus or minus two standard errors of estimate of the mean.

Erskine et al (2001) recommended that the results of the baseline program in the Ngarradj catchment should be reviewed after a minimum of 3 years to determine the strengths and weaknesses of the program. Such a review of the erosion pin program is included in this report. The aims of the present work are:

- To outline the erosion pin program in the Ngarradj catchment;
- To present the results for the first three years of field measurements between the 1998/1999 wet season and 2001 dry season;
- To determine the magnitude, variability and causes of bank erosion and deposition at the erosion pin sites;
- To analyse the erosion pin data; and
- To review the requirements and nature of a continued erosion pin program.

2 A review of the erosion pin method

Erosion pins have been used to measure gully nickpoint retreat, hillslope erosion and soil creep (Ireland et al 1939, Emmett 1965, Haigh 1977, Loughran 1989, Saynor et al 1994) as well as bank erosion rates on river channels and gullies (Wolman 1959, Twidale 1964, Hooke 1979, Crouch 1987, Neller 1988, Erskine et al 1995). Erosion pins or iron rods were originally used by Ireland et al (1939) to determine rates of plunge pool cutting at the head of gullies in South Carolina, USA. Wolman (1959) pioneered the use of pins to measure bank erosion rates on an actively migrating, meandering stream near Baltimore, USA. However, Hudson (1982) criticised the pin technique for measuring bank erosion and proposed a new method based on detailed bank profiling. While such profiling is a worthwhile method for measuring erosion rates on banks with complex forms, it was not adopted for this project for the following five reasons:

1. The baseline program at Jabiluka was designed, initiated and implemented at short notice before the start of the 1998/1999 wet season following the Commonwealth Government's approval of uranium mining in August 1998.

2. There was insufficient time for the construction of the Hudson (1982) bank profiler before the start of the bank erosion program at Jabiluka. It was essential to collect pre-wet season benchmark data to assess post-mining changes.
3. There was insufficient time for the installation of baselines at multiple bank erosion sites on multiple streams before the 1998/1999 wet season for the use of bank profiling.
4. Complex bank profiles with frequent undercuts were not common on the Jabiluka Mining Lease (see below).
5. A large number of erosion pins could be installed at multiple sites on multiple streams in the Jabiluka Mining Lease in the short time available before the start of the 1998/1999 wet season.

The erosion pin technique is based on the principle that a pin is inserted into a bank, leaving a known length exposed to provide a benchmark against which subsequent erosion can be measured (Couper et al 2002). Haigh (1977) and Couper et al (2002) identified the following four problems with the method:

1. An assumption of the technique is that the pin is stationary. While frost action can disturb pins (Couper et al 2002), this is not an issue in the tropics. However, active erosion can totally remove pins, necessitating careful treatment of the resultant data (Erskine et al 1995).
2. The bank can advance and retreat independently of erosion and deposition (Haigh 1977) due to shrink/swell following moisture changes, heating during the day and cooling at night, wetting and drying, freezing and thawing and/or cyclic hydration of clay minerals (Couper et al 2002). The present study is conducted in sandy sediments (see below) where the shrink/swell potential is minimal.
3. The presence of the pin or the insertion of the pin into the bank can disturb natural geomorphic processes. Rusting of pins can also bind soil, changing the rate of erosion (Bridges & Harding 1971).
4. Humans can interfere with pins but this is not likely on the Jabiluka Mining Lease because of restricted access and because stakeholders have been well informed of ***eriss***'s programs (Erskine et al 2001). However, feral animals (particularly pigs) are common and may disturb pins close to the river bed.

Hooke (1979) found that pins performed well in river banks composed of silty alluvial material and suggested that they were much less suitable for gravelly banks. More recently, Couper et al (2002) found that negative erosion-pin data were common in three catchments in the United Kingdom. While they identified a number of potential processes that can cause such a result, deposition was *not* the most likely cause, unlike in other studies (for example, Saynor et al 1994, Erskine et al 1995). Couper et al (2002) recommended that studies using erosion pins should state:

- Whether or not negative recordings were obtained, and if so, potential causes suggested by field observations, and
- How negative data were treated in the data analysis.

We agree with Couper et al (2002) and have followed their recommendations below.

Lawler (1993) undertook a detailed review of the various methods of measuring river bank erosion and concluded that pins were a simple, cheap, sensitive method suitable for a wide range of fluvial environments. The use of pins is popular for determining amounts and rates of bank erosion for these reasons. Lawler (1993) and Couper et al (2002) also maintained that pins are a point-specific technique whose results need to be treated with great care before deriving areal, volumetric or gravimetric estimates of bank retreat, such as required for a sediment budget. Mean bank retreat values are often associated with very high coefficients of variation (Lawler 1993). For this reason, we cite the standard error of estimate of the mean for all values. The nature and magnitude of errors associated with the use of pins must be considered in the manner discussed by Haigh (1977) and Lawler (1993). Their recommendations are also followed below.

3 Methods

3.1 Field methods

Erosion pins were installed during the late dry season of 1998 on the mine site streams, Tributaries North and Central (fig 1). Additional erosion pins were installed during the late dry season of 1999 near each ***eriss*** gauging station in the Ngarradj catchment at the same cross sections as the scour chains (Saynor et al 2002b). In most instances, pins were installed on both banks where they were nearly vertical (> 70°) or steeply sloping (between 25° and 70°). If the bank was gently sloping (< 25°), such as on the inside of a bend with a well developed point bar, then pins were not installed. In the Ngarradj catchment, a vertical spacing between pins of between 0.1 and 0.3 m (Wolman 1959, Hooke 1979, 1980, Couper et al 2002) was adopted because it captured the geomorphic detail of the river banks at a resolution that was adequate to enable identification of erosional and depositional processes and rates. The number of pins installed on each bank profile was determined with regard to minimising the impact of field measurements on bank erosion in sandy sediments (see section 4).

Following the recommendations of Lawler (1993), erosion pins were 6 mm diameter metal rods, approximately 300 mm long and painted white in an attempt to reduce the amount of corrosion or rust (Bridges & Harding 1971). Nevertheless, pins still rusted, cementing sand to the pin and reducing the reliability of the bank retreat measurements. Generally 30–50 mm of the pin was left exposed to assist recovery. The amount of exposure of each erosion pin was measured (fig 2) during the early dry season and then again just before the next wet season. When necessary, pins were reset or replaced before the onset of the wet season. A greater frequency of measurements during the wet season was impossible because of prolonged flooding (usually at least three and sometimes five months) of the only access road and because of the presence of saltwater crocodiles (*Crocodylus porosus*) in Ngarradj. Crocodiles episodically damaged the inlet pipes to the float well at the Ngarradj gauge (SM in fig 1).

Erosion pins were always installed at existing cross sections because they could be easily relocated and because they provided data on small-scale erosion rates at tacheometrically surveyed sites where large-scale erosion rates were also being measured. Table 1 lists the location and total number of pins installed at each cross section at each site and further details are contained in Saynor et al (2001). Erosion pins were always measured on the top of the pin with a flat-edged stainless steel ruler (fig 2) as soon as access was possible after the wet season. Pin exposure was not changed at this time. Local experience with pin measurements has shown maximum errors of ± 2 mm, due to finding and measuring the pins. This is a conservative estimate and is based on the difficulties of measuring the amount of pin exposure in coarse sand which is the dominant bank material (see below). A metal detector was used (fig 3) to find buried pins or those obscured by vegetation. The detector was purchased in 1999 and greatly improved the relocation of buried pins thereafter. Buried pins were replaced with new pins, often leading to problems of correct pin identification, if both were subsequently re-exposed.

Erosion is always denoted by positive values and deposition by negative values, when presenting erosion pin results (Wolman 1959, Hooke 1979, 1980, Saynor et al 1994, Couper et al 2002). This convention has been followed here. Furthermore, erosion pins often experience negative values or deposition, as recorded elsewhere in Australia by Saynor et al (1994) and Erskine et al (1995).

The net erosion or deposition on each bank profile is determined by calculating the arithmetic mean of the measured values for each profile for each season of each year. Negative values are included in all of the following calculations. Negative values were caused by deposition of sand on the exposed pin or rust-binding of sand to the pin. Deposition was caused by sand being dislodged higher up the bank and accumulating as micro-scree slopes at the base of the bank (see below for further details). For buried pins, deposition is assumed to have occurred to the end of the formerly exposed pin. This is a minimum estimate of deposition because it is impossible to determine the actual amount without physically disturbing the bank. If a pin was buried during the wet season it was not assessed at the end of the following dry season (except if it was re-exposed). This can lead to an underestimation of deposition rates. For completely eroded pins, the amount of erosion is assumed to be a maximum of 250 mm, which is slightly less than the total length of the erosion pin. Where the pin had not been reset before being completely eroded, the previously measured amount of exposure was subtracted from 250 mm. The amount of bank retreat/deposition is shown as the absolute change between successive measurements. One standard error of estimate of the mean is shown as the plus and minus value following the mean erosion amount.

Bank form refers to the cross sectional shape or sidewall profile and has been described in the field for each erosion pin site using the following classification scheme (modified from Crouch 1987, Crouch & Blong 1989) which is illustrated in fig 5:

1. Vertical bank (> 70º).
2. Steeply sloping bank (essentially constant angle between 25° and 70°).
3. Gently sloping bank (essentially constant angle < 25°)
4. Convex bank (upper bank element less steep than lower bank).
5. Concave bank (upper bank element steeper than lower bank).
6. Composite bank (various combinations of three or more facets, such as steeply sloping over vertical over steeply sloping or gently sloping over vertical over steeply sloping).

There are many potential composite bank profiles with only four of the most common shown in fig 5. Bank profile form has been shown to significantly influence erosion rates elsewhere (Crouch 1987) and must be considered in any study of bank erosion.

The location of each erosion pin site was also described in the field in terms of which bank (left or right looking downstream) of the stream and channel planform. The following terms were adequate to describe planform:

1. Upstream limb of bend.
2. Bend apex.
3. Downstream limb of bend.
4. Straight reach.
5. Channel constriction.

Table 1 Erosion pins installed in the Ngarradj catchment in 1998 and 1999. See fig 1 for location of channels and see subsequent sections for detailed location diagrams of each cross section.

Location and Cross Section	Bank	Proximity to Cross Section	Number of Pins
Tributary North 1998			
TN01	Right	2 m upstream	3
TN02	Left	2–4 m upstream	3
TN03	Left	2 m upstream	4
TN04	Right	13 m downstream	3
TN04 Tributary	Right	Just upstream	3
TN05	Right	2 m upstream	3
TN06 Tributary	Left	2 m downstream	3
TN07	Right	2 m downstream	3
TN07 Tributary	Right	2 m upstream	3
TN08	Left	2 m upstream	4
TN08 Tributary	Right	2–3 m upstream	4
TN09	Right	1–2 m upstream	4
TOTAL	**All Sites**		**40**
Tributary North 1999			
TN01	Right	8–9 m upstream	3
TN01	Left	9–10 m upstream	3
TN03	Right	2 m upstream	3
TN04 Tributary	Left	Just upstream	3
TOTAL	**All Sites**		**12**
Tributary Central 1998			
TC01	Right	2 m downstream	3
TC03	Right	3 m downstream	3
TC04	Left	Just downstream	4
TC05	Right	1–2 m downstream	5
TC06B	Left	On section	4
TC07B	Right	Just upstream	7
TC08	Left	3 m upstream	6
TC09	Right	1 m downstream	5
TC09	Right	2 m upstream	4
TC10	Right	1 m downstream	4
TOTAL	**All Sites**		**45**
Tributary Central 1999			
TC01	Right	On section	3
TC06A	Left	1 m upstream	5
TC06C	Left	2 m downstream	3
TC07A	Right	Just upstream	6
TC07B	Right	1 m upstream	5
TC07C	Right	2 m downstream	4
TC08	Left	3 m upstream	4
TOTAL	**All Sites**		**30**

Table 1 continued

Location and Cross Section	Bank	Proximity to Cross Section	Number of Pins
East Tributary 1999			
ET01	Right	On section	4
ET01	Left	On section	3
ET04	Right	On section	4
ET04	Left	On section	3
ET07	Left	On section	4
ET08	Left	On section	4
TOTAL	**All Sites**		**22**
Swift Creek 1999			
SM05	Right	On section	5
SM02	Right	On section	3
SM08	Right	On section	5
SM08	Left	On section	3
TOTAL	**All Sites**		**16**
Upper Swift Creek 1999			
UM02	Right	On section	4
UM02	Left	On section	5
UM05	Right	On section	4
UM05	Left	On section	7
UM07	Right	On section	4
UM07	Left	On section	4
TOTAL	**All Sites**		**28**
TOTAL of Erosion Pins at all locations			**193**

3.2 Statistical analyses

Simple statistical tests were employed because the data did not warrant more sophisticated analyses. The F test was used to determine whether the variances of erosion pin measurements were significantly different between seasons and years at each site and for each stream, between different bank profile forms and between different channel planforms for each year. Then the relevant version of the t test (ie either for equal or unequal variances, depending on the results of the F test) was used to assess the significance of changes in means between seasons and years, where the data were not significantly skewed. A one tailed test was used for differences in means between wet and dry seasons because little erosion was expected during the dry season when there was no streamflow (see below). A two-tailed test was used for differences in means between years because there was no a priori reason for bank erosion to differ between years (all three years experienced above average rainfall – see below). A paired t test was not used because there was never a constant number of paired pin measurements at each site due to burial and subsequent re-exposure of pins. The test of Matalas and Benson (1968) was used to determine whether the calculated coefficient of skewness of the erosion pin data exceeded twice the standard error of estimate and hence was significantly skewed. The t test is robust to violations of normality but is sensitive to skewed data (Mitchell et al 1966). Therefore, the above approach was adopted instead of testing for normality. For skewed data, the nonparametric Mann-Whitney test was used to determine changes in populations instead of in means. While it is a nonparametric substitute for the t test it determines whether two samples came from the same population (Davis 1986).

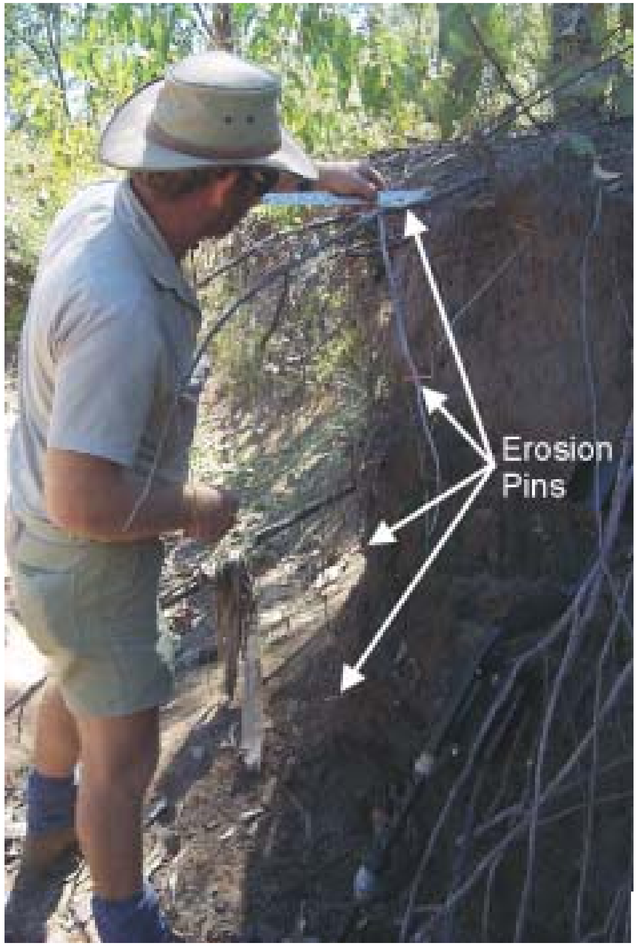

Figure 2 Measurement of erosion pins on Tributary Central at cross section TC6B during the dry season. Metal detector is resting against the bank. Vertical bank profile on the outside of a meander loop.

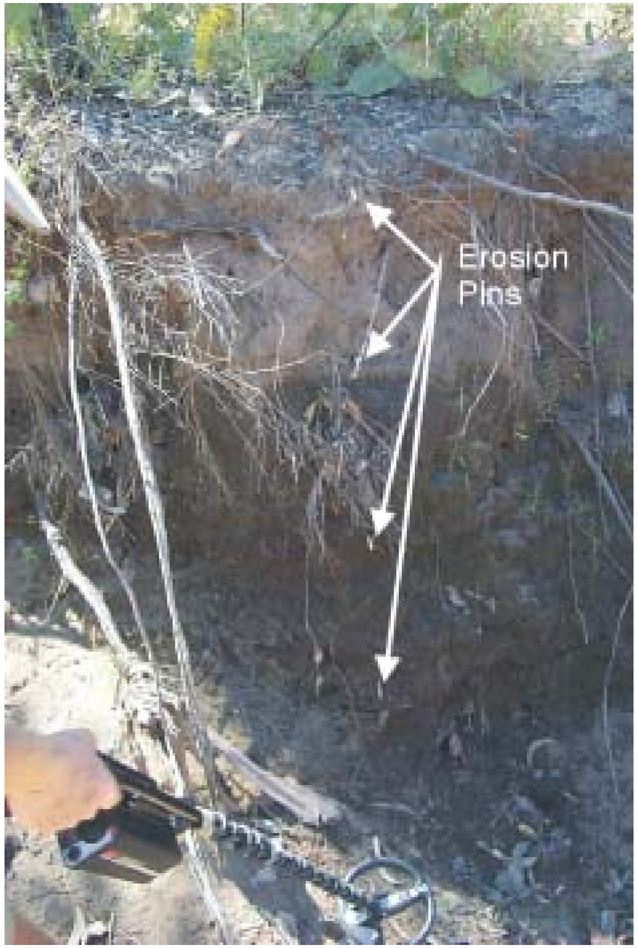

Figure 3 Metal detector used to relocate buried pins. Tributary Central cross section TC6B during the dry season when the water table is at least 0.5 m below the river bed. Bank profile is vertical. Compare with wet season conditions in fig 4.

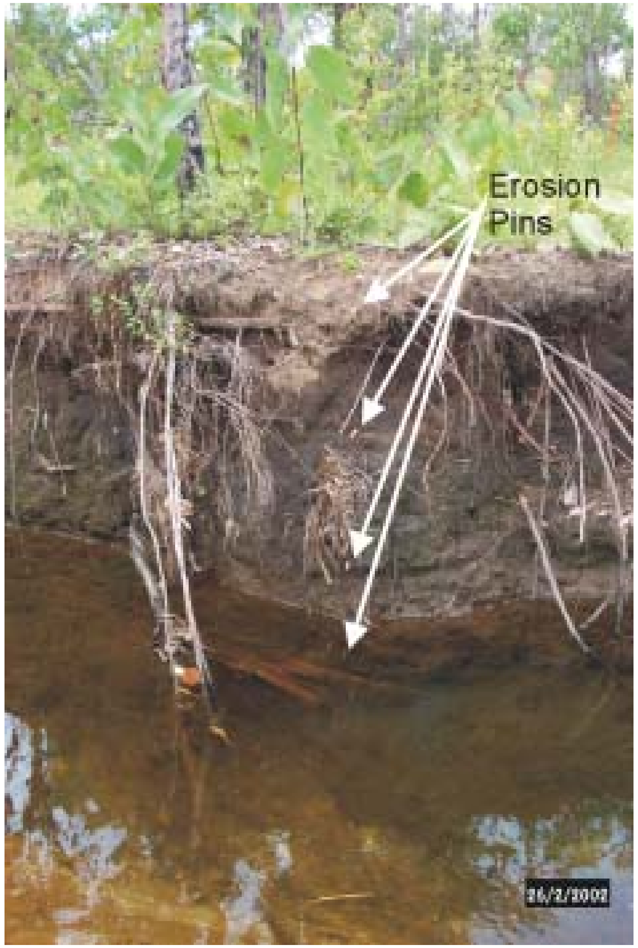

Figure 4 Same bank as in fig 3 during wet season baseflows

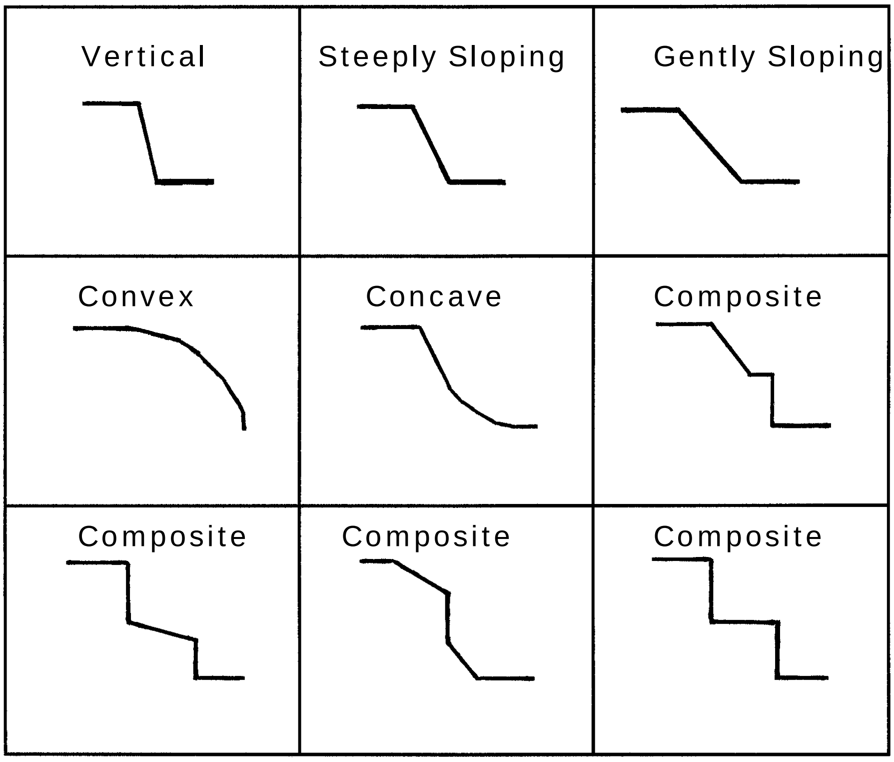

Figure 5 Classification scheme used to describe bank profile form at the erosion pin sites in the Ngarradj catchment. Additional types of composite bank profiles are possible.

4 Study sites and catchment hydrology

The purpose of this section is to outline the site characteristics, bank sediments and hydrology during the measurement period. Erosion pins were installed at the three ***eriss*** gauging stations (fig 1) which are located in Erskine et al's (2001) Forested Meandering Reach (upper Swift Creek), Sinuous Reach (Swift Creek) and Forested Meandering Reach (East Tributary). The respective catchment areas are 18.8, 43.6 and 8.5 km^2. The two Forested Meandering Reaches are continuously flanked by dense riparian vegetation and the Sinuous Reach is also characterised by riparian vegetation which, although less dense than in the two upstream reaches, still stabilises the banks against fluvial erosion (Erskine et al 2001). Erosion pins were also installed in Erskine et al's (2001) Gullied Reach on Tributary North and in their Sinuous Reach, Large Capacity Reach and Small Capacity Reach on Tributary Central. Both of these channels do not have a riparian vegetation community and the river banks are consequently less protected by living vegetation, roots and root mats than at the gauging stations. The total catchment areas of Tributary North and Tributary Central are 0.6 and 2.5 km^2 respectively.

The bank (floodplain) sediments in the Ngarradj catchment have been described by Erskine et al (2003) and, with the exception of site 6 on Tributary Central (figures 2, 3 & 4), are all sandy. According to Folk's (1974) textural classification scheme, the bank sediments at the Swift Creek gauge ranged between clayey medium-coarse sand at depth to muddy fine-very fine sand near the surface. At the upper Swift Creek gauge, the left bank sediments ranged from medium-coarse sand at depth to muddy fine sand at the surface. On the right bank, sediments ranged from pebbly clayey coarse sand at depth to muddy medium sand at the surface. Bedrock (iron-indurated sandstone) was present close to the river bed along the right bank and was exposed in the lower 0.3 m of the bank at cross section 1. At the East Tributary gauge, the left bank sediments ranged from slightly pebbly coarse sand at depth to muddy fine sand at the surface. On the right bank, sediments ranged from medium-coarse sand at depth to muddy medium-coarse sand at the surface. In the gullied reach of Tributary North, bank sediments ranged from slightly granular muddy medium sand at depth to slightly granular medium sand at the surface. The bank sediments on Tributary Central became finer textured downstream in relation to the sand fraction (coarse sand to fine sand) although the bank sediments at site 6 were muddy sand. Complete profile descriptions of each sediment layer (colour and texture) at each site are contained in Erskine et al (2003).

Rainfall is highly seasonal in the Ngarradj catchment with monthly totals greater than 150 mm being recorded at the peak of the wet season between December and March (Moliere et al 2002). Much lower totals are recorded during both the build up to (September to November), and the recession from (April and May), the wet season. Little rainfall is usually recorded between June and August. The earliest rainfall during the bank erosion measurements was recorded on 20 September (1998) and the latest rainfall was recorded on 24 May (2000) (Moliere et al 2002). Erosion pin measurements were conducted between late 1998 and 2001 when rainfall was above average. Moliere et al (2002) estimated that the average recurrence intervals for annual rainfall for the 1998/1999, 1999/2000 and 2000/2000 water years were 1:13, 1:71 and 1:21 years respectively.

The seasonal streams gauged by ***eriss*** (fig 1) commenced flowing on 8 November (1999) at the earliest (streamflow did not persist after this first flush and recommenced on 20 November 1999) but usually on or after 20 November each year. The amount of rainfall before streamflow commenced was approximately 430, 280 and 250 mm for the 1998/1999, 1999/2000 and 2000/2001 water years respectively (Moliere et al 2002). Streamflow persisted until between May and July each year (Moliere et al 2002). The largest peak instantaneous discharges were recorded during the 1998/1999 wet season but the variation between years was minor (Moliere et al 2002).

Figures 3 and 4 compare the same bank profile between wet and dry seasons. Bank sediments are at least episodically saturated because bankfull discharge occurred at least once during each wet season (Moliere et al 2002). During the dry season, all channels ceased flowing and the water table dropped to at least 0.6 m below the river bed (Saynor et al 2002b). These extreme soil moisture conditions occurred every year and should be conducive to bank erosion because of severe desiccation where there is no riparian vegetation.

5 Results

The erosion pin data are discussed below for the two mine site tributaries and for each gauging station reach (fig 1). Pin 1 is always the highest and the largest pin number refers to the one closest to the river bed.

5.1 Tributary North

Erosion pins are located on nine cross sections of the main gully of Tributary North and on four cross sections of the lower tributary (table 1 & fig 6) in the gullied reach of Erskine et al (2001).

5.1.1 Lower Gully of Tributary North

The erosion pin results are shown in table 2. Cross sections are always presented in the table of results in sequential order from upstream to downstream.

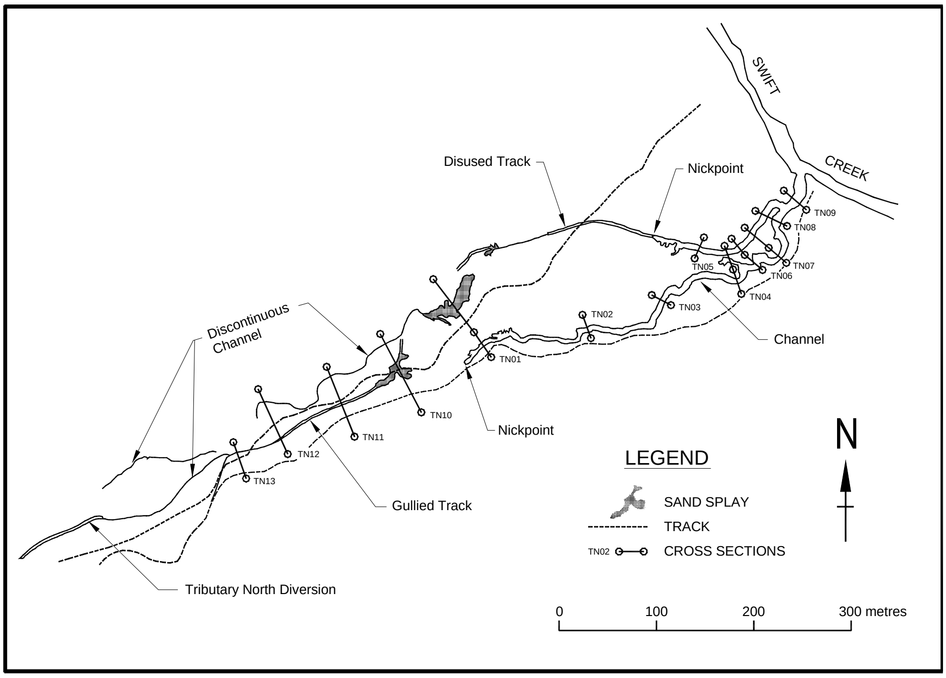

Figure 6 Location of the permanently marked cross sections on Tributary North

After the 1998/1999 wet season, 54% (13 of the 24 pins) exhibited erosion, 4% (1) no change and 42% (10 with 2 pins completely buried) deposition. Mean net change for all pins was 16 ± 10 mm, maximum bank retreat was 195 mm and maximum deposition was -34 mm. For the 1999 dry season, 64% (14) of the pins exhibited erosion and 36% (8) deposition. Mean net change was 11 ± 8 mm, maximum bank retreat was 141 mm and maximum deposition was -23 mm. Variances were not significantly different ($\rho = 0.196$) between the wet and dry seasons and there was no significant difference in means ($\rho = 0.326$).

After the 1999/2000 wet season, 33% (10 of the 30 pins) exhibited erosion, 3% (1) no change and 63% (19 with 6 pins completely buried) deposition. Mean net change for all pins was 5 ± 8 mm, maximum bank retreat was 153 mm and the maximum deposition was -47 mm. For the 2000 dry season, 48% (11) exhibited erosion, 17% (4) no change and 35% (8) deposition. Mean net change was 1 ± 8 mm, maximum bank retreat was 98 mm and maximum deposition was -110 mm. Variances were not significantly different ($\rho = 0.425$) between the wet and dry seasons and there was no significant difference in means ($\rho = 0.353$).

After the 2000/2001 wet season, 45% (13 of the 29 pins with 2 completely removed) exhibited erosion, 3% (1) no change and 52% (15) deposition. Mean net change for all pins was 12 ± 10 mm, maximum bank retreat was 217 mm and maximum deposition was -55 mm. For the 2001 dry season, 33% (9) of the pins exhibited erosion, 7% (2) no change and 59% (16) deposition. Mean net change was 8 ± 6 mm, maximum bank retreat was 145 mm and maximum deposition was -30 mm. Variances were significantly different ($\rho = 0.02$) between the wet and dry seasons but the difference in means was not significant ($\rho = 0.380$).

Bank retreat did not vary systematically with bank form although convex banks recorded a higher frequency of deposition. Table 3 shows the probability levels for differences in variances and means between wet seasons and between dry seasons. There were no significant differences between the variances and the means for any of the combinations of years.

Table 2 Erosion pin results (mm) for Tributary North main gully. Pins were initially installed in November and December 1998.

Location		8-Jun-99 wet season	17-Nov-99 dry season	9-Aug-00 wet season	1-Dec-00 dry season	09-Jul-01 wet season	14-Nov-01 dry season	Bank Form	Planform
TN01	1	9	7	210	N/M	N/M	N/M	Concave	Straight Reach
RB*	2	54	92	78	N/M	N/M	N/M		
1st	3	60	141	14	N/M	N/M	N/M		
	Mean	41	80	101	N/A	N/A	N/A		
Standard Error		16	39	58	N/A	N/A	N/A		
TN01	1	N/M	N/M	20	6	43	145	Concave	Straight Reach
RB*	2	N/M	N/M	153	0	57	N/M		
2nd	3	N/M	N/M	22	13	-20	-34		
	Mean	N/A	N/A	65	6	27	56		
Standard Error		N/A	N/A	44	4	24	90		
TN01	1	N/M	N/M	86	-64	20	1	Concave	Straight Reach
LB	2	N/M	N/M	88	74	35	5		
	3	N/M	N/M	1	98	-48	-4		
	Mean	N/A	N/A	58	36	2	1		
Standard Error		N/A	N/A	29	50	26	3		
TN02	1	34	12	84	-110	101	-5	Convex	D/S Limb of Bend
LB	2	86	2	75	14	51	68		
	3	195	15	-29	0	217	N/M		
	Mean	105	10	43	-32	123	32		
Standard Error		47	4	36	39	49	37		
TN03	1	13	-15	9	1	-1	-17	Convex	Straight Reach
LB	2	5	-8	-8	-1	-7	14		
	3	-5	-3	-8	-14	-5	-3		
	4	6	-1	-39	N/M	-16	-22		
	Mean	5	-7	-12	-5	-7	-7		
Standard Error		3	2	9	5	3	9		
TN03	1	N/M	N/M	2	17	0	-30	Steeply Sloping	Straight Reach
RB	2	N/M	N/M	-5	-2	2	18		
	3	N/M	N/M	-36	N/M	-55	20		
	Mean	N/A	N/A	-13	8	-18	3		
Standard Error		N/A	N/A	12	10	19	16		
TN04	1	41	3	-47	-11	-55	10	Convex	Bend Apex
RB	2	-28	N/M	-12	-30	9	7		
	3	-26	N/M	-40	N/M	60	13		
	Mean	-4	3	-33	-21	5	10		
Standard Error		23	N/A	11	10	33	2		

Table 2 continued

Location		8-Jun-99 wet season	17-Nov-99 dry season	9-Aug-00 wet season	1-Dec-00 dry season	09-Jul-01 wet season	14-Nov-01 dry season	Bank Form	Planform
TN07	1	0	4	-1	0	-3	0	Convex	Straight Reach
RB	2	-12	-10	-26	N/M	N/M	N/M		
	3	-18	4	-18	N/M	-26	10		
	Mean	-10	-1	-15	0	-15	5		
Standard Error		5	5	7	N/A	12	5		
TN08	1	15	-23	-27	N/M	-24	-3	Convex	Bend Apex
LB	2	-34	10	-21	N/M	5	3		
	3	-20	10	-20	23	-13	14		
	4	-1	1	-5	7	-4	3		
	Mean	-10	-1	-18	15	-9	4		
Standard Error		11	8	5	8	6	4		
TN09	1	28	-8	-12	0	2	7	Steeply Sloping	U/S Limb of Bend
RB	2	5	7	-18	4	-2	2		
	3	-10	0	0	-5	24	0		
	4	-4	-6	-4	1	-3	2		
	Mean	5	-2	-9	0	5	3		
Standard Error		8	3	4	2	6	1		

* – Location changed
N/M – Not Measured
N/A – Not Available

Table 3 Probability levels for differences between wet and dry season variances (F test) and means (t test) for each combination of water years

Wet season	1998/99 v 1999/00	1999/00 v 2000/01	1998/99 v 2000/01
F test	0.702	0.500	0.818
t Test (2 tails)	0.402	0.622	0.748
Dry Season	1999 v 2000	2000 v 2001	1999 v 2001
F test	0.724	0.399	0.643
t Test (2 tails)	0.393	0.473	0.814

5.1.2 Tributary gully of lower Tributary North

The results are shown in table 4 and the location of the cross sections is shown in figure 6.

After the 1998/1999 wet season, 69% (11 of the 16 pins) exhibited erosion and 31% (5 with 1 pin completely buried) deposition. Mean net change for all pins was 8 ± 7 mm, maximum bank retreat was 79 mm and maximum deposition was -29 mm. For the 1999 dry season, 40% (6) of the pins exhibited erosion and 60% (9) deposition. Mean net change was -2 ± 3 mm, maximum bank retreat was 10 mm and maximum deposition was -34 mm. Variances were significantly different (ρ = 0.002) between the wet and dry seasons but the difference in means (ρ = 0.071) was not significant.

Table 4 Erosion pin results (mm) for the tributary gully of lower Tributary North. Pins were initially installed in November and December 1998.

Location		8-Jun-99 wet season	17-Nov-99 dry season	9-Aug-00 wet season	1-Dec-00 dry season	09-Jul-01 wet season	14-Nov-01 dry season	Bank Form	Planform
TN04	1	-4	-15	25	23	35	-1	Steeply Sloping	Bend Apex
RB	2	-8	-1	-24	N/A	19	12		
	3	10	-1	-31	13	-12	6		
	Mean	-1	-6	-10	18	14	6		
Standard Error		5	5	18	5	14	4		
TN04	1	N/M	N/M	-12	5	26	20	Steeply Sloping	U/S Limb of Bend
LB	2	N/M	N/M	-44	5	-6	-7		
	3	N/M	N/M	-42	N/A	12	-6		
	Mean	N/A	N/A	-33	5	11	2		
Standard Error		N/A	N/A	10	0	9	9		
TN05	1	79	-34	62	-1	-58	19	Steeply Sloping	Straight Reach
RB	2	3	-5	58	-41	34	8		
	3	8	-1	-20	6	-14	-7		
	Mean	30	-13	33	-12	-13	7		
Standard Error		25	10	27	15	27	8		
TN06	1	10	1	-4	3	-6	6	Concave	D/S Limb of Bend
RB	2	9	7	-24	-16	-56	N/A		
	3	23	7	-27	-20	-57	-10		
	Mean	14	5	-18	-11	-40	-2		
Standard Error		5	2	7	7	17	8		
TN07	1	26	-1	4	-7	2	-16	Steeply Sloping	D/S Limb of Bend
RB	2	-29	N/A	-12	1	-18	-2		
	3	-21	1	-12	5	-8	7		
	Mean	-8	0	-7	0	-8	-4		
Standard Error		17	1	5	4	6	7		
TN08	1	41	10	-5	-24	-25	8	Steeply Sloping	U/S Limb of Bend
RB	2	7	3	-9	-21	-19	-6		
	3	-24	-2	2	-6	14	-26		
	4	5	-6	-10	-3	-16	8		
	Mean	7	1	-6	-14	-12	-4		
Standard Error		13	3	3	5	9	8		

N/M – Not Measured.

N/A – Not Available

Table 5 Probability levels for differences in variances and means between wet and dry season measurements for each combination of water years for the tributary gully of Tributary North

Wet seasons	**1998/99 v 1999/00**	**1999/00 v 2000/01**	**1998/99 v 2000/01**
F test	0.757	0.965	0.789
t Test (2 tails)	0.117	0.874	0.085
Dry Seasons	1999 v 2000	2000 v 2001	1999 v 2001
F test	0.150	0.278	0.660
t Test (2 tails)	0.661	0.265	0.427

After the 1999/2000 wet season, 26% (5 of the 19 pins) exhibited erosion and 74% (14 with 2 pins completely buried) deposition. Mean net change for all pins was -7 ± 7 mm, maximum bank retreat was 62 mm and maximum deposition was -44 mm. For the 2000 dry season, 47% (8) of the pins exhibited erosion and 53% (9) deposition. Mean net change was -5 ± 4 mm, maximum bank retreat was 23 mm and maximum deposition was -41 mm. Variances were significantly different ($\rho = 0.020$) between the wet and dry seasons but the difference in means ($\rho = 0.397$) was not significant.

After the 2000/2001 wet season, 37% (7 of the 19 pins) exhibited erosion and 63% (12) deposition. Mean net change for all pins was -8 ± 6 mm, maximum bank retreat was 35 mm and maximum deposition was -58 mm. For the 2001 dry season, 50% (9) of the pins exhibited erosion and 50% (9) deposition. Mean net change was 1 ± 3 mm, maximum bank retreat was 20 mm and maximum deposition was -26 mm. Variances were significantly different ($\rho = 0.001$) between the wet and dry seasons but the difference in means ($\rho = 0.113$) was not significant.

All but one bank profile was steeply sloping so it was not possible to determine variations in bank erosion with profile form. Table 5 shows the probability levels for the differences in the variances and means between wet and dry seasons for each year of measurements. There was no significant difference in variances and means for any of the combinations of years for each season.

5.2 Tributary Central

Erosion pins are located at nine sites on Tributary Central (table 6). Three cross sections were installed at two sites (cross sections TC06A, B and C and TC07A, B and C) where there are well-developed meander loops in Erskine et al's (2001) sinuous reach. Erosion pins are located on the left bank of all three cross sections at TC06 (TC06A, B & C) which is the most upstream section (fig 8). The left bank is the concave bank of a small radius bend with a well developed point bar on the inside bank and with a bedrock rapid exposed in the bed immediately downstream of the bend (fig 8). Erosion pins are located on the right bank of the three cross sections at TC07 (TC07A, B & C) which is also the concave bank of a small radius bend. The erosion pin data are shown in table 6 and the location of the cross sections is shown in fig 7.

Table 6 Erosion pin results (mm) for Tributary Central. Pins were initially installed in November and December 1998.

Location		8-Jun-99 wet season	16-Nov-99 dry season	9-Aug-00 wet season	1-Dec-00 dry season	9-Jul-01 wet season	14-Nov-01 dry season	Bank Form	Planform
TC06A	1	N/M	N/M	20	25	0	-5	Vertical	U/S Limb of Bend
LB	2	N/M	N/M	-1	0	-1	0		
	3	N/M	N/M	-1	7	-7	3		
	4	N/M	N/M	-8	-14	-9	N/A		
	5	N/M	N/M	-45	N/A	-69	N/A		
	Mean	N/A	N/A	-7	5	-17	-1		
Standard Error		N/A	N/A	11	8	13	2		
TC06B	1	-2	1	31	9	168	N/A	Vertical	Bend Apex
LB	2	-2	9	-2	0	210	N/A		
	3	6	7	-2	-1	209	N/A		
	4	23	1	-1	-4	208	N/A		
	Mean	6	5	7	1	199	N/A		
Standard Error		6	2	8	3	10	N/A		
TC06C	1	N/M	N/M	215	N/A	198	N/A	Concave	D/S
LB	2	N/M	N/M	214	N/A	194	N/A		Limb of
	3	N/M	N/M	206	N/A	190	N/A		Bend
	Mean	N/A	N/A	212	N/A	194	N/A		
Standard Error		N/A	N/A	3	N/A	2	N/A		
TC07A	1	230	N/A	226	N/A	33	65	Concave	Bend
	2	210	N/A	212	N/A	-3	0		Apex
RB	3	215	N/A	194	N/A	-20	2		
	4	221	N/A	205	N/A	-2	4		
	5	222	N/A	197	N/A	-10	3		
	6	226	N/A	216	N/A	Only 5 pins reinstalled			
	7	215	N/A	Only 6 pins installed					
	Mean	220	N/A	208	N/A	0	15		
Standard Error		3	N/A	5	N/A	9	13		
TC07B	1	N/M	N/M	205	N/A	207	N/A	Composite: (Vertical/ Steeply Sloping/ Gently Sloping)	D/S Limb of Bend
RB	2	N/M	N/M	208	N/A	205	N/A		
	3	N/M	N/M	203	N/A	198	N/A		
	4	N/M	N/M	195	N/A	23	177		
	5	N/M	N/M	201	N/A	Only 4 pins reinstalled			
	Mean	N/A	N/A	202	N/A	158	N/A		
Standard Error		N/A	N/A	2	N/A	45	N/A		
TC07C	1	N/M	N/M	7	2	206	N/A	Concave	D/S Limb of Bend
RB	2	N/M	N/M	0	-2	217	N/A		
	3	N/M	N/M	-9	-1	120	4		
	4	N/M	N/M	-39	N/A	43	0		

	Mean	N/A	N/A	-10	0	147	2		
Standard Error		N/A	N/A	10	1	41	2		
TC08	1	127	5	1	-5	57	11	Composite: (Steeply Sloping/ Gently Sloping/ Steeply Sloping)	Straight Reach
LB	2	53	2	29	-58	149	14		
	3	-5	3	3	-1	-32	N/A		
	4	-7	1	-30	14	-14	N/A		
	5	6	N/A	N/A	N/A	N/A	N/A		
	6	225	N/A	N/A	N/A	N/A	N/A		
	Mean	67	3	1	-13	40	13		
Standard Error		38	1	12	16	41	2		
TC08	1	N/M	N/M	-18	0	-5	14	Composite: (Steeply Sloping/ Gently Sloping/ Steeply Sloping)	Straight Reach
RB	2	N/M	N/M	-34	26	-44	N/A		
	3	N/M	N/M	-9	0	-18	N/A		
	4	N/M	N/M	-38	N/A	-20	29		
	Mean	N/A	N/A	-25	9	-22	22		
Standard Error		N/A	N/A	7	9	8	8		
TC09	1	220	N/A	4	0	213	N/A	Composite: (Vertical/ Steeply Sloping/ Vertical)	D/S Limb of Bend
RB	2	30	104	102	14	209	N/A		
	3	205	N/A	-36	N/A	2 pins	2 pins		
	4	-3	2	9	13	-201	N/A		
	5	29	-5	30	5	27	3		
	Mean	96	34	22	8	62	N/A		
Standard Error		48	35	23	3	98	N/A		
TC10	1	219	N/A	228	N/A	31	N/A	Composite: (Steeply Sloping/ Undercut/	U/S Limb of Bend (oncave)
LB	2	225	N/A	224	N/A	25	N/A		
	3	223	N/A	-33	N/A	27	N/A		
	4	206	N/A	-37	N/A	Only 3 pins reinstalled			
	Mean	218	N/A	96	N/A	28	N/A		
Standard Error		4	N/A	75	N/A	2	N/A		
TC05	1	-4	4	68	19	2	5	Composite: (Vertical/ Steeply Sloping/ Vertical)	Straight Reach
RB	2	-35	N/A	-5	-1	-4	2		
	3	-36	N/A	8	6	4	12		
	4	-22	N/A	29	-19	13	1		
	5	-35	N/A	Not reinstalled					
	Mean	-26	N/A	25	1	4	5		
Standard Error		6	N/A	16	8	4	2		
TC11	1	227	N/A	-8	-1	234	N/A	Concave	Bend Apex
RB	2	230	N/A	53	33	195	N/A		
	3	216	N/A	69	18	193	N/A		
	4	219	N/A	-38	N/A	201	N/A		
	Mean	223	N/A	19	17	206	N/A		

Standard Error		3	N/A	25	10	10	N/A		
TC04	1	53	-1	-19	0	-4	2	Concave	Straight Reach
LB	2	-2	-1	-5	1	-5	2		
	3	-5	-3	-4	2	49	15		
	4	94	-57	-38	25	-12	-5		
	Mean	35	-16	-17	7	7	4		
Standard Error		24	14	8	6	14	4		
TC03	1	6	-4	1	-4	6	3	Concave	Straight Reach
RB	2	-2	-14	8	-12	-8	N/A		
	3	-65	N/A	-41	N/A	-40	N/A		
	Mean	-20	-9	-11	-8	-14	N/A		
Standard Error		22	5	15	4	14	N/A		
TC01	1	6	N/A	159	6	17	3	Concave	Constriction
RB	2	234	N/A	78	-19	40	-2		
	3	-19	N/A	-40	N/A	112	-6		
	Mean	74	N/A	66	-7	56	-2		
Standard Error		80	N/A	58	13	29	3		

N/M – Not Measured.

N/A – Not Available

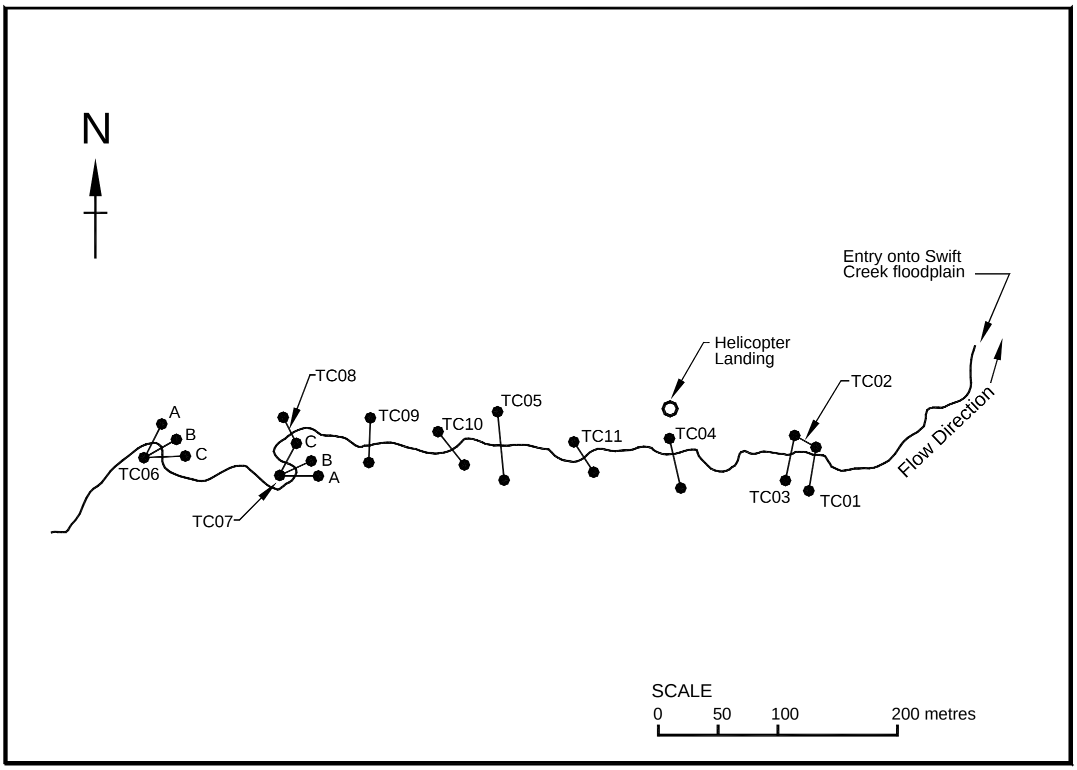

Figure 7 Location of the permanently marked cross sections on Tributary Central

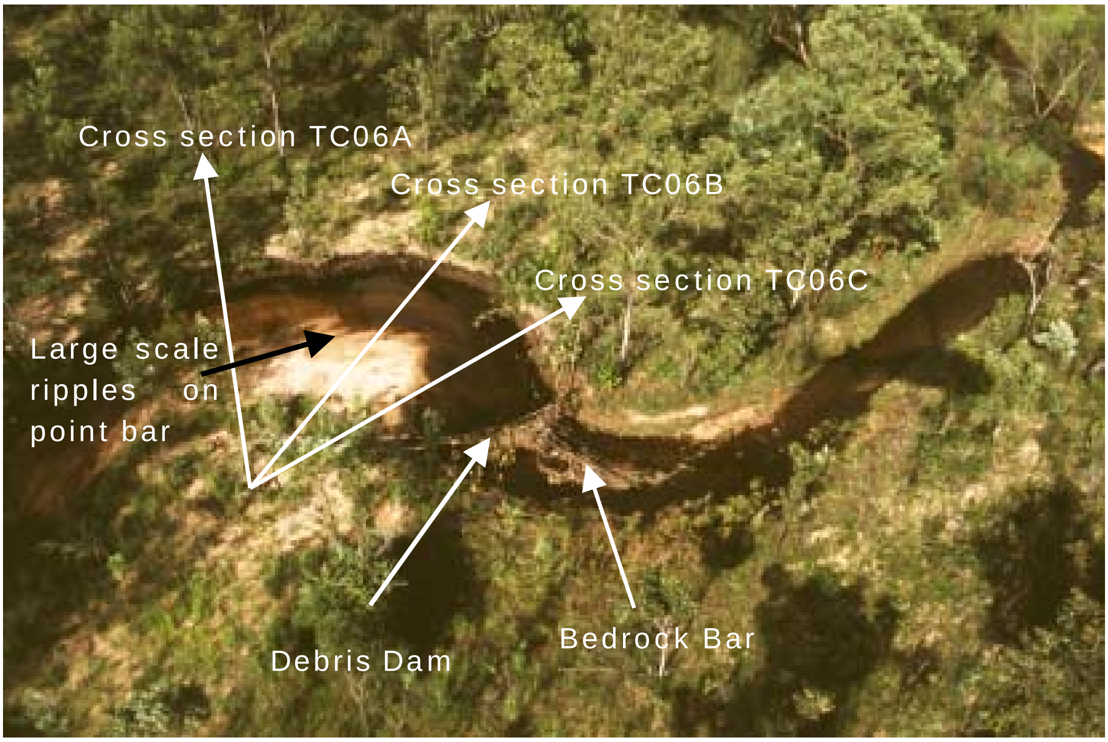

Figure 8 Cross sections TC06A, B and C on a loop of Tributary Central, showing a large sandy point bar opposite the erosion pin sites and a debris dam downstream of the sites at the head of a bedrock bar

After the 1998/1999 wet season, 67% (30 of the 45 pins with 20 completely eroded) exhibited erosion and 33% (15 with 6 pins completely buried) deposition. Mean net change for all pins was 97 ± 17 mm, maximum bank retreat was 234 mm and maximum deposition was -65 mm. For the 1999 dry season, 61% (11) of the pins exhibited erosion and 39% (7) deposition. Mean net change was 3 ± 7 mm, maximum bank retreat was 9 mm and maximum deposition was -57 mm. Variances were significantly different ($\rho < 0.0001$) between the wet and dry seasons but there was no significant difference in populations according to the Mann-Whitney U test.

After the 1999/2000 wet season, 56% (35 of the 62 pins with 16 completely removed) exhibited erosion, 2% (1) no change and 42% (26 with 11 pins completely buried) deposition. Mean net change for all pins was 3 ± 7 mm, maximum bank retreat was 228 mm and maximum deposition was -45 mm. For the 2000 dry season, 46% (17) of the pins exhibited erosion, 16% (6) no change and 38% (14) deposition. Mean net change was 2 ± 6 mm, maximum bank retreat was 33 mm and maximum deposition was -58 mm. Variances were significantly different ($\rho < 0.0001$) between the wet and dry seasons but there was no significant difference in populations according to the Mann-Whitney U test.

After the 2000/2001 wet season, 62% (36 of the 58 pins with 22 pins completely removed) exhibited erosion, 2% (1) no change and 36% (21 with 8 pins completely buried) deposition. Mean net change for all pins was 67 ± 13 mm., maximum bank retreat was 234 mm and maximum deposition was -69 mm. For the 2001 dry season, 75% (21) of the pins exhibited erosion, 11% (3) no change and 14% (4) deposition. Mean net change was 13 ± 7 mm, maximum bank retreat was 177 mm and maximum deposition was -6 mm. Variances were significantly different ($\rho < 0.0001$) between the wet and dry seasons but there was no significant difference in populations according to the Mann-Whitney U test.

Bank retreat did not vary systematically with bank profile form although there is a large amount of missing data (table 6). Table 7 shows the probability levels for differences in variances and means/populations between years for each season. There were no significant changes for the wet seasons. Variances between the 1999 and 2000, and 2000 and 2001 dry seasons were significantly different but there were no significant changes in means/populations for any combinations of dry seasons (table 7).

Table 7 Probability levels for differences in variances and means between wet and dry season measurements for each combination of water years for Tributary Central

Wet season	1998/99 v 1999/00	1999/00 v 2000/01	1998/99 v 2000/01
F test	0.350	0.705	0.5683
t Test (2 tails)/Mann-Whitney U test	0.593	0.562	0.724
Dry Season	1999 v 2000	2000 v 2001	1999 v 2001
F test	0.002	0.001	0.127
t Test (2 tails)/Mann-Whitney U test	0.919	0.103	0.368

5.3 East Tributary

Erosion pins are located on four of the cross sections, ET01, ET04, ET07 and ET08 (fig 9). The results of the erosion pin measurements are shown in table 8.

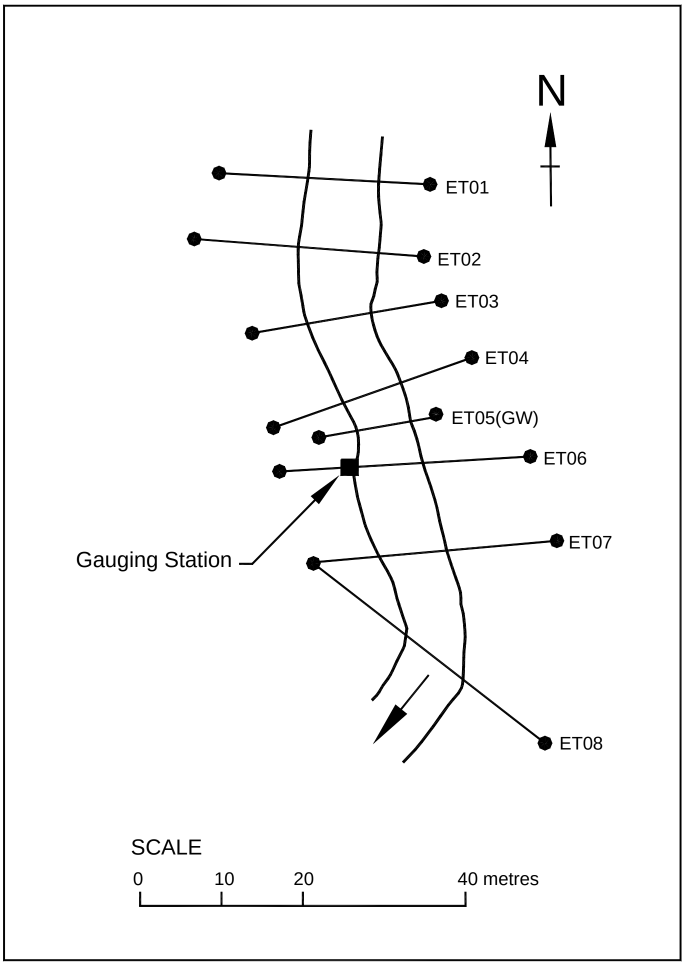

Figure 9 Location of the cross sections on East Tributary at the ***eriss*** gauging station

Table 8 Erosion pin results (mm) for East Tributary. Pins were initially installed on 3 November 1999

Location		1-Aug-00 wet season	1-Dec-00 dry season	9-Jul-01 wet season	14-Nov-01 dry season	Bank Form	Planform
ET01	1	68	-34	68	1	Convex	D/S Limb of Bend
RB	2	-14	13	27	-3		
	3	0	1	-3	0		
	4	-3	7	-1	1		
	Mean	13	-3	23	0		
	Standard Error	19	11	17	1		
ET01	1	-5	1	-1	2	Convex	D/S Limb of Bend
LB	2	5	-1	1	0		
	3	-1	1	-3	1		
	Mean	0	0	-1	1		
	Standard Error	3	1	1	1		
ET04	1	0	0	-7	1	Steeply Sloping	D/S Limb of Bend
RB	2	-10	0	6	-1		
	3	18	-9	14	-3		
	4	14	15	-19	17		
	Mean	6	2	-2	4		
	Standard Error	6	5	7	5		
ET04	1	18	-2	17	7	Composite: (Gently Sloping/ Steeply Sloping/ Gently Sloping)	D/S Limb of Bend
LB	2	4	2	0	-1		
	3	29	0	-4	-1		
	Mean	17	0	4	2		
	Standard Error	7	1	6	3		
ET07	1	1	-3	4	1	Concave	Straight Reach
LB	2	-10	2	-3	3		
	3	13	-11	11	-1		
	4	-6	8	-7	-3		
	Mean	-1	-1	1	0		
	Standard Error	5	4	4	1		
ET08	1	0	0	-3	0	Composite: (Gently Sloping/ Steeply Sloping/ Horizontal/ Steeply Sloping)	Bend Apex
LB	2	2	0	0	1		
	3	7	1	30	1		
	4	28	-7	14	0		
	Mean	-9	3	10	-1		
	Standard Error	7	-1	-8	0		

After the 1999/2000 wet season, 55% (12 of the 22 pins) exhibited erosion, 9% (2) no change and 36% (8) deposition. Mean net change for all pins was 7 ± 4 mm, maximum bank retreat was 68 mm and maximum deposition was -14 mm. For the 2000 dry season, 50% (11) of the pins exhibited erosion, 18% (4) no change and 32% (7) deposition. Mean net change for all pins was -1 ± 2 mm, maximum bank retreat was 15 mm and maximum deposition was

-34 mm. Variances were significantly different (ρ = 0.0054) for the wet and dry seasons but the difference in populations was not significant.

After the 2000/2001 wet season, 45% (10 of the 22 pins) exhibited erosion, 9% (2) no change and 45% (10) deposition. Mean net change for all pins was 6 ± 4 mm, maximum bank retreat was 68 mm and maximum deposition was -19 mm. For the 2001 dry season, 50% (11) of the pins exhibited erosion, 14% (3) no change and 36% (8) deposition. Mean net change for all pins was 1 ± 1 mm, maximum bank retreat was 17 mm and maximum deposition was -3 mm. Variances were significantly different (ρ < 0.0001) between the wet and dry seasons but the difference in populations was not significant.

Bank retreat was minor for all bank profile forms. Variances and differences in populations between the two wet seasons were not significantly different (ρ = 0.953 and 0.947, respectively). Variances between successive dry seasons were significantly different (ρ = 0.0004) but the difference in populations was not significant (ρ = 0.302).

5.4 Upper Swift Creek

Erosion pins are located on three cross sections, UM02, UM05 and UM07 (fig 10). The results are shown in table 9. Pins at cross section UM07 were not measured on 1 December 2000, hence values for 9 July 2001 have been compared with those for 1 August 2000 (table 9).

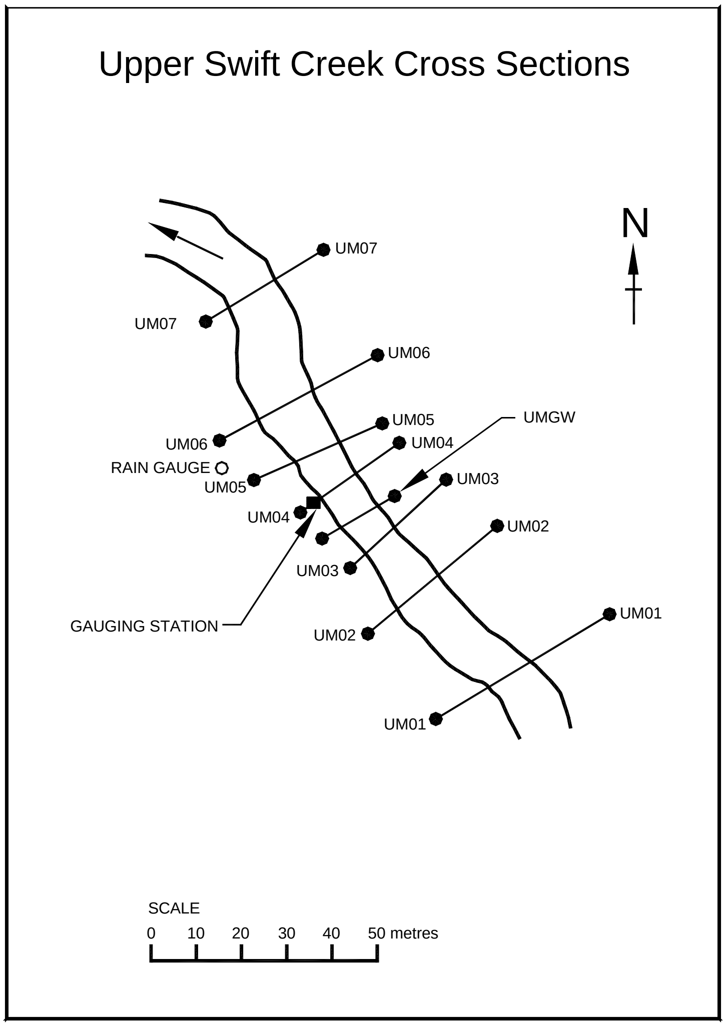

Figure 10 Location of the cross sections at the upper Swift Creek gauge

Table 9 Erosion pin results (mm) for upper Swift Creek. Pins were initially installed on 3 November 1999.

Location		1-Aug-00 wet season	1-Dec-00 dry season	9-Jul-01 wet season	14-Nov-01 dry season	Bank Form	Planform
UM02	1	-24	-13	8	0	Convex	Straight Reach U/S of Constriction
RB	2	-31	18	40	-28		
	3	-4	3	-17	16		
	4	-5	13	-20	-15		
	Mean	-16	5	3	-7		
	Standard Error	7	7	14	9		
UM02	1	-53	-8	14	1	Steeply Sloping	Straight Reach U/S of Constriction
LB	2	-33	5	9	-10		
	3	-16	7	0	3		
	4	-8	11	2	10		
	4	-2	26	-52[B]	N/A[B]		
	Mean	-22	8	-5	1		
	Standard Error	9	5	12	4		
UM05	1	2	11	-9	-2	Convex	Straight Reach
RB	2	7	1	4	0		
	3	-12	4	-6	6		
	4	4	2	0	4		
	Mean	0	5	-3	2		
	Standard Error	4	2	3	2		
UM05	1	33	-2	13	-21	Composite: (Gently Sloping/ Steeply Sloping/ Gently Sloping)	Straight Reach
LB	2	8	3	-7	6		
	3	17	2	17	0		
	4	-18	10	11	-4		
	5	-2	1	2	0		
	6	0	4	-26	3		
	7	-11	-2	20	11		
	Mean	4	2	4	-1		
	Standard Error	7	2	6	4		
UM07	1	3	Not Measured	-4	-3	Composite: (Steeply Sloping/ Vertical/ Steeply Sloping)	Bend Apex
RB	2	10		8	0		
	3	-5		1	3		
	4	24		-13	3		
	Mean	8		-2	1		
	Standard Error	6		4	1		
UM07	1	15	Not Measured	-4	8	Convex	Bend Apex
LB	2	-3		-2	1		
	3	-28		5	12		
	4	-20		19	13		
	Mean	-9		5	9		
	Standard Error	10		5	3		

B in the table indicates that a pin was buried and thus shows minumum deposition only. The buried pin could not then be considered in the subsequent calculation and is denoted by N/A.

After the 1999/2000 wet season, 36% (10 of the 28 pins) exhibited erosion, 4% (1) no change and 60% (17) deposition. Mean net change for all pins was 5 ± 3 mm, maximum bank retreat was 33 mm and maximum deposition was -53 mm. For the 2000 dry season the pins on cross section 8 were not measured and thus only 20 pins were used for the calculations. Of the 20 pins, 80% (16) exhibited erosion and 20% (4) deposition. Mean net change for all pins was 5 ± 2 mm, maximum bank retreat was 26 mm and maximum deposition was -13 mm. Variance was significantly different ($\rho = 0.0012$) between the wet and dry seasons and the difference in means was also significant ($\rho = 0.0071$, 1 tail).

The pins on cross section 8 have been compared with the values for the pins on 1 August 2000 for the 2000/2001 wet season. After the 2000/2001 wet season, 54% (15 of the 28 pins) exhibited erosion, 7% (2) no change, 36% (10) deposition and 3% (1) were completely buried. Mean net change for all pins was 0 ± 3 mm, maximum bank retreat was 40 mm and maximum deposition was -52 mm. For the 2001 dry season, 56% (15) of the pins exhibited erosion, 19% (5) no change, and 27% (7) deposition. Mean net change for all pins was 1 ± 1 mm, maximum bank retreat was 16 mm and maximum deposition was -28 mm. Variances were significantly different ($\rho = 0.007$) for the wet and dry seasons but the difference in means was not significant ($\rho = 0.485$, 1 tail).

Bank retreat was minor for all bank profile forms. Variances and means between wet seasons were not significantly different ($\rho = 0.677$ and $\rho = 0.220$, 2 tailed respectively). The same result was obtained for dry seasons ($\rho = 0.554$ and $\rho = 0.140$, 2 tails for F- and t-test respectively).

5.5 Swift Creek

Erosion pins are located on three cross sections, SM05, SM02 and SM08 (fig 11). The results are shown in table 10.

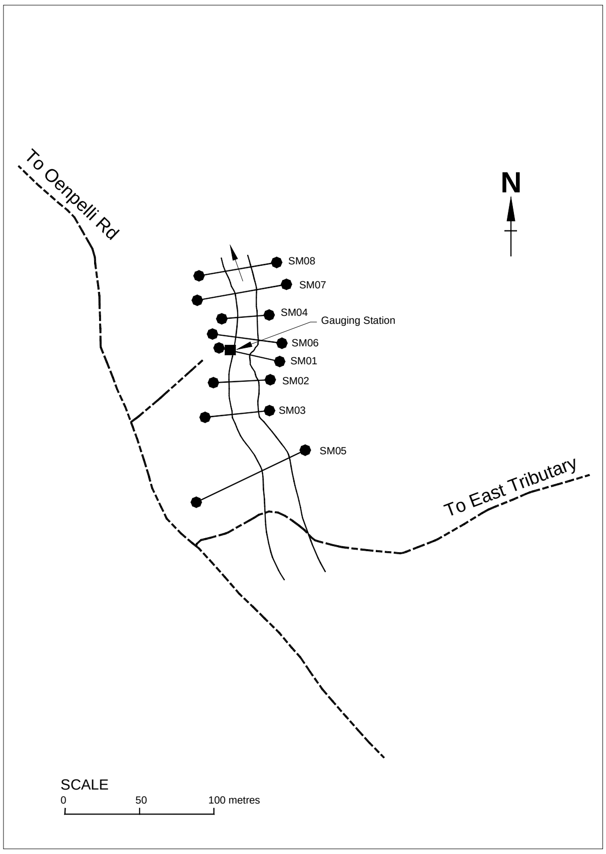

Figure 11 Location of cross sections at the lower Swift Creek gauge

Table 10 Erosion pin results (mm) for Swift Creek. Pins were initially installed on 3 November 1999.

Location		1-Aug-00 wet season	1-Dec-00 dry season	9-Jul-01 wet season	14-Dec-01 dry season	Bank Form	Planform
SM05	1	-23	6	-25	6	Convex	Bend Apex
RB	2	-60	N/A	-40	N/A		
	3	-5	1	67	0		
	4	-41	N/A	16	N/D		
	5	-72	N/A	9	-6		
	Mean	-40	4	5	0		
	Standard Error	12	3	19	3		
SM02	1	-26	-36	-36	N/A	Steeply Sloping	Bend Apex
RB	2	111	1	-13	5		
	3	-51	N/A	81	-1		
	Mean	11	-18	11	2		
	Standard Error	50	19	36	3		
SM08	1	-27	-20	-2	N/A	Steeply Sloping	Straight Reach
RB	2	-21	10	-40	N/A		
	3	-42	N/A	-51	9		
	4	133	70	40	11		
	5	-29	N/A	-63	N/A		
	Mean	3	20	-23	10		
	Standard Error	33	32	19	1		
SM08	1	-45	N/A	N/A	N/A	Steeply Sloping	Straight Reach
LB	2	-36	N/A	N/A	N/A		
	3	87	-147	87	-11		
	Mean	2					
	Standard Error	43					

ND – Not determined; pin re-exposed

N/A – Pin buried after wet season so not used for dry season calculations

After the 1999/2000 wet season, 19% (3 of the 16 pins) exhibited erosion, 31% (5) deposition and 50% (8) were buried. Mean net change for all pins was -9 ± 4 mm, maximum bank retreat was 133 mm and maximum deposition was -72 mm. For the 2000 dry season only the values for 8 pins could be calculated as the other 8 pins were buried. Of the 8 exposed pins, 62.5% (5) exhibited erosion and 37.5% (3) deposition. Mean net change for all pins was -14 ± 7 mm, maximum bank retreat was 70 mm and maximum deposition was -147 mm. Variances were not significantly different (ρ = 0.946) between the wet and dry seasons and there was no significant difference in populations.

The pins at cross section 8 were not reinstalled prior to the 2000/2001 wet season and thus only the bottom pin could be used in the calculations because it was re-exposed. Therefore, only 14 pins were used in the following calculations. After the 2000/2001 wet season, 43% (6 of the 14 pins) exhibited erosion, 21% (3) deposition and 36% (5) were completely buried. Mean net change for all pins was 2 ± 4 mm, maximum bank retreat was 87 mm and maximum deposition was -63 mm. For the 2001 dry season, only 9 pins could be used in the calculations as the other 5 were still buried. Of the 9 exposed pins, 44% (4) exhibited erosion, 11% (1) no change, 33% (3) deposition and 11% (1) could not be determined as a previously buried pin was re-exposed. Mean net change for all pins was 2 ± 1 mm, maximum bank retreat was 11 mm and maximum deposition was -11 mm. Variances were significantly different ($\rho < 0.0001$) for the wet and dry seasons but the difference in means was not significant ($\rho = 0.489$, 1 tail).

Bank retreat was minor for all bank profile forms. Variances between successive wet seasons were not significantly different ($\rho = 0.438$) and the difference in populations was also not significant. Variances between successive dry seasons were significantly different ($\rho < 0.0001$) but the difference in means was not significant ($\rho = 0.490$, 2 tails).

5.6 Bank erosion summary for 1998 to 2001

The average bank retreat/advance for each wet and dry season between 1998 and 2001 for each measurement reach is summarised in table 11. The main results are:

- As expected, bank erosion is usually greater during the wet than the dry season;
- Bank erosion also occurs during many dry seasons when there is no streamflow and this sediment is readily available for transport by the first flush event of the succeeding wet season;
- Net bank deposition often occurs during the wet season;
- Bank erosion is very active on Tributary Central and, to a lesser degree, on the main gully on lower Tributary North; and
- Bank erosion is very minor in the ***eriss*** gauging station reaches.

Clearly, the most active channel is Tributary Central which has a number of rapidly migrating bends (Saynor et al 2002a). Figure 12 shows this rapid lateral migration on three bends as determined by the repeated survey of permanently marked cross sections (Saynor et al 2002a). The retreat of these bends is often that rapid that pins are totally removed (fig 13). Therefore, the cross sections should be adequate to determine future rapid bank retreat on migrating bends. These bends developed by lateral migration before the commencement of the Jabiluka mine. The present measurements all relate to the period after the establishment of the mine. Therefore, the historical set of vertical air photographs should be analysed to determine longer-term lateral migration rates on Tributary Central, to which the current rates can be compared.

Tributary North, in the lower gullied reach of Erskine et al (2001), is the second most active channel although the tributary gully, which eroded along a former track (Saynor et al 2002a), is relatively stable. While the nickpoint at the upstream limit of the gully is eroding upstream at about 2 m/year (Saynor et al 2002a), the sidewalls are also retreating. The cause of sidewall erosion is a combination of basal undercutting by within-gully flows and surficial erosion of the coherent topsoil by overland flow plunging into the gully over the sidewalls. The coherent topsoil often exhibits vertical grooves or flute marks eroded by overland flow.

Deposition is an active process on the river banks in the Ngarradj catchment. While this is often the case on mud-dominated rivers (Schumm 1960, Woodyer et al 1979, Erskine & Melville 1982), the channels discussed here are sand-bed streams with very low mud loads by world standards (Erskine & Saynor 2000). Erskine and Livingstone (1999) documented rapid sand deposition on in-channel benches where sand-bed streams were recovering from massive channel enlargement by catastrophic floods. However, this is also not the case in the Ngarradj catchment. Localised fluvial deposition of sand on banks is often caused by eddies associated with large woody debris or large-scale boundary roughness associated with riparian vegetation in the forested meandering reaches of Erskine et al (2001). Furthermore, erosion during the dry season can dislodge sediment that is partially deposited on pins lower down the bank. Figures 14 and 15 show bank erosion during the dry season due to localised faunal activity. On one bank, black-headed pardalotes (*Pardalotus melanocephalus*) made nests which a sand goanna (*Varanus gouldii*) tried to access (fig 14). Claw marks can be clearly seen in the bank in fig 15. This dislodged sediment was deposited on some lower pins. Bank sediment was also very dry during the late dry season and the resultant loss of cohesion of the coarse sands often resulted in dry sand flow on steep banks (fig 16). Sand dislodged from dry river banks often accumulated as micro-scree slopes at the base of the bank during the dry season, completely burying erosion pins (fig 16).

Bank deposition was also caused by conveyance losses involving the complete infiltration of overland flow moving down gently sloping river banks. Intense convective rain storms during the build up to the wet season often generated Hortonian overland flow (rainfall intensity greater than soil infiltration rate) on the floodplain and river banks which was exacerbated by strongly hydrophobic (water repellent) surface soils, especially following dry season fires in 1998 and 1999. Overland flow which passed over sandy channel banks, caused local erosion of the upper banks and deposition on the lower banks. These corresponded to small-scale scour-transport-fill (STF) sequences, up to 5 m long, which are similar to, but smaller, than those described by Pickup (1985, 1988) and Saynor et al (1994). Figures 17 and 18 show such STF sequences on the river banks at the Swift Creek gauge in December 2001. STF processes can cause erosion at pins in the upper scour zone and can result in deposition over pins in the lower fill zone, where infiltration into dry, deep sand can totally absorb the Hortonian overland flow (figs 17 & 18).

The bank retreat data in table 11 have been combined with the cross section results and the differential GPS maps of the measurement reaches (figs 6, 7, 9, 10 & 11) to compute the seasonal sediment generation rates in terms of mass for each measurement reach in table 12. The following assumptions were made:

- The average bank retreat amounts in table 11 are representative of each measurement reach;
- Sediment bulk density is uniform at 1.5 t/m^3;
- The average bank height for each measurement reach derived from the cross sections in Saynor et al (2002a) is representative of the reach; and
- There are two banks, one on each side of the channel, throughout the measurement reaches so that the centre line distances measured by differential GPS were multiplied by two.

Table 11 Summary of bank erosion results (mm) for the Ngarradj catchment between 1998 and 2001

	1998/1999 wet season	1999 dry season	1999/2000 wet season	2000 dry season	2000/2001 wet season	2001 dry season
Tributary North Main Gully	16 ± 10	11 ± 8	5 ± 11	1 ± 8	12 ± 10	8 ± 6
Tributary North Tributary Gully	8 ± 7	-2 ± 3	-7 ± 7	-5 ± 4	-8 ± 6	1 ± 3
Tributary Central	97 ± 17	3 ± 7	57 ± 11	2 ± 6	67 ± 13	13 ± 7
East Tributary	N/M	N/M	7 ± 4	-1 ± 2	6 ± 4	1 ± 1
Upper Swift Creek	N/M	N/M	-5 ± 3	5 ± 2	0 ± 3	1 ± 2
Swift Creek	N/M	N/M	-9 ± 4	-14 ± 7	2 ± 4	2 ± 1
Mean	40 ± 28	4 ± 4	8 ± 10	-2 ± 3	13 ± 11	4 ± 2

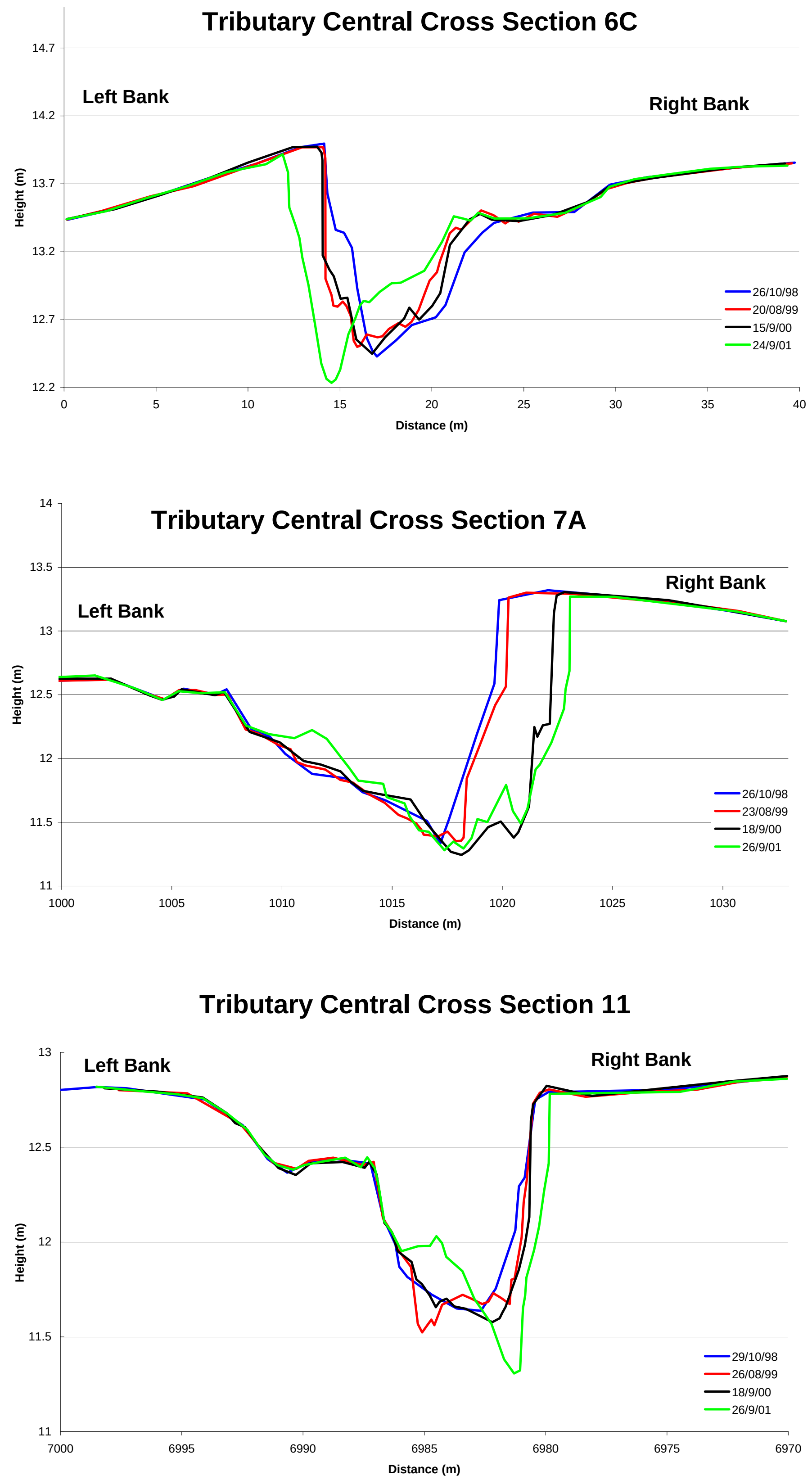

Figure 12 Recent lateral migration of three bends on Tributary Central. See fig 7 for the location of the sections and Saynor et al (2002a) for further details.

Figure 13 Completely eroded pins on cross section TC07A on 27 February 2002. See fig 7 for the location of the cross section.

It must be emphasised that the sediment masses in table 12 only refer to the measurement reaches which vary in length from 65 to 681 m and have no estimates have been made for the whole channel network in the Ngarradj catchment. As total channel length is much greater than the measurement reaches, the total sediment contribution by bank erosion throughout the Ngarradj channel network is much greater than the reach estimates in table 12. Nevertheless, bank erosion alone can supply significant amounts of sediment for fluvial transport in channels without riparian vegetation in the Ngarradj catchment. Furthermore, sediment delivery processes do not have to be considered because the material is already in the channel. However, deposition will temporarily store some of this sediment within the channel network. This is especially the case in the depositional reaches identified by Erskine et al (2001), namely the Braided Floodout reach, Fan Delta Reach and Terminal Wetland Reach on Ngarradj; *Melaleanca* Swamp Reach on Tributary West; Grassed Depression Reach on Tributary South; and Small Capacity Reach on Tributary Central. The net export of sediment into Magela floodplain from Ngarradj is very low because of the extensive sediment storage for sand and mud in the three reaches on lower Ngarradj mentioned above.

Table 12 Summary of sediment generated by bank erosion (tonnes) for the Ngarradj catchment in the measurement reaches only between 1998 and 2001

	1998/1999 wet season	1999 dry season	1999/2000 wet season	2000 dry season	2000/2001 wet season	2001 dry season
Tributary North Main Gully	25.4	17.5	8.2	1.6	19.1	12.7
Tributary North Tributary Gully	2.9	-0.7	-2.6	-1.8	-2.9	0.4
Tributary North Total for lower Gullied Reach	28.3	16.8	5.6	-0.2	16.2	13.1
Tributary Central	276	8.5	162	5.7	190	36.9
East Tributary	N/M	N/M	2.3	-0.3	2.0	0.3
Upper Swift Creek	N/M	N/M	-9.0	-14.0	2.0	2.0
Swift Creek	N/M	N/M	-6.2	-9.7	1.4	1.4

Figure 14 Bank burrow on Tributary Central near cross section TC07A which has resulted in the localised loss of sand from the face of the bank during the dry season. Note sandy micro-scree slope at base of bank which has formed by the accumulation of sand dislodged from immediately above.

Figure 15 Faunal scratch marks on the right bank of Tributary Central near cross section TC07A which have removed sediment from the bank face during the dry season. Note sandy micro-scree slope at base of bank which has formed by the accumulation of sand dislodged from the bank above by scratching and desiccation.

Figure 16 Sandy micro-scree slope formed by the dry flow of sand down the right bank of Tributary Central near cross section TC07A

Figure 17 Micro-fan deposited at the base of the river bank at the ***eriss*** Swift Creek gauge by infiltration of Hortonian overland flow into the sand. The fan is the fill zone of a small-scale scour-transport-fill sequence.

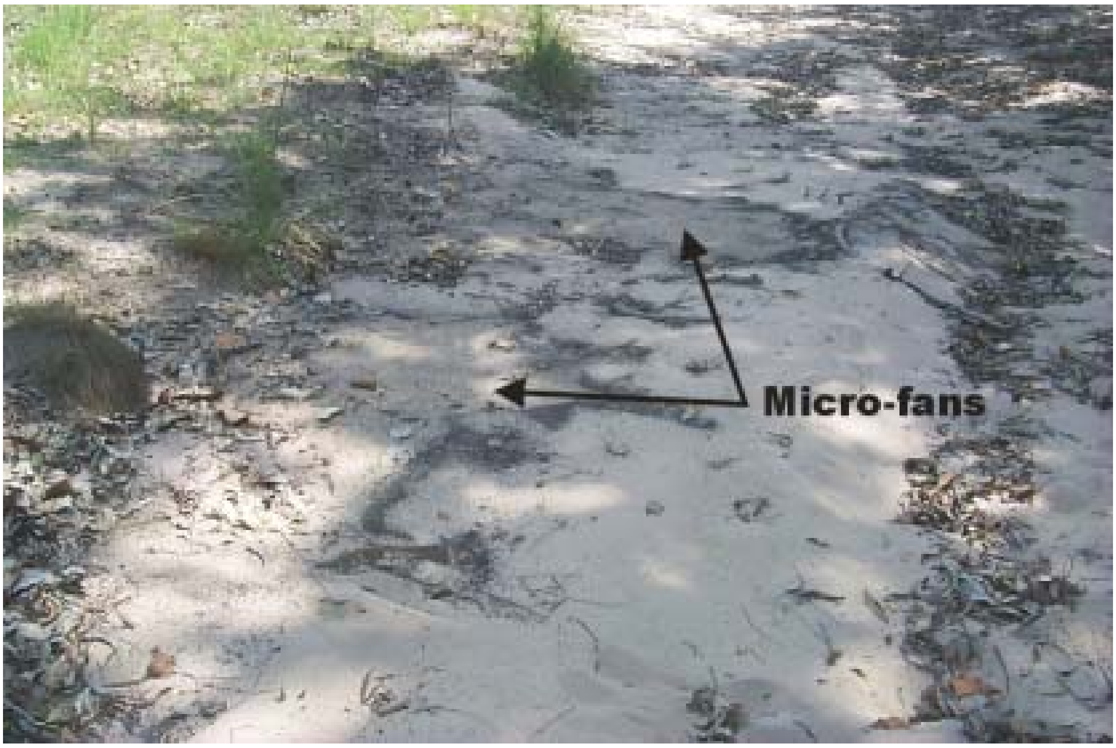

Figure 18 Two micro-fans deposited at the base of the river bank at the ***eriss*** Swift Creek gauge by infiltration of Hortonian overland flow into the sand. The fans are the fill zones of small-scale scour-transport-fill sequences.

6 Factors influencing bank erosion

To determine the effects of bank profile form (fig 5) and channel planform (the five fold classification on p 6) on bank erosion rates, the data for all sites were reclassified according to these two factors and analysed separately for each season for each year, as above. The results are presented in the following two subsections.

6.1 Bank profile form effects on bank erosion

Bank profile form effects on bank erosion should be greatest during the wet season when streamflow, raindrop impact and overland flow are active. No pins were installed on gently sloping banks. For the wet season, of the 60 statistical tests, the following 31 were significant ($\rho \leq 0.05$):

- Significant differences in the variances and populations for 1998/99 and 1999/2000 between vertical and concave banks (139 v 11749 mm^2 for 1998/99 and 432 v 8923 mm^2 for 1999/2000 for variances; 6 v 107 mm for 1998/99 and -1 v 58 for 1999/2000 for means).
- Significant differences in the variances and populations for 1998/99 and 1999/2000 between vertical and composite banks (139 v 11867 mm^2 for 1998/99 and 432 v 6413 mm^2 for 1999/2000 for variances; 6 v 81 mm for 1998/99 and -1 v 37 for 1999/2000 for means).
- Significant differences in the variances and populations for 1998/99, 1999/2000 and 2000/01 between steeply sloping and concave banks (686 v 11749 mm^2 for 1998/99, 1464 v 8923 mm^2 for 1999/2000 and 1038 v 8174 mm^2 for 2000/01 for variances; 7 v 107 mm for 1998/99, -4 v 58 for 1999/2000 and -2 v 54 for 2000/01 for means).
- Significant differences in the variances and populations for 1998/99, 1999/2000 and 2000/01 between steeply sloping and composite banks (686 v 11867 mm^2 for 1998/99, 1464 v 6413 mm^2 for 1999/2000 and 1038 v 9916 mm^2 for 2000/01 for variances; 7 v 81 mm for 1998/99, -4 v 37 for 1999/2000 and -2 v 44 for 2000/01 for means).
- Significant differences in the variances and populations for 1998/99, 1999/2000 and 2000/01 between convex and concave banks (3032 v 11749 mm^2 for 1998/99, 920 v 8923 mm^2 for 1999/2000 and 2251 v 8174 mm^2 for 2000/01 for variances; 15 v 107 mm for 1998/99, -9 v 58 for 1999/2000 and 11 v 54 for 2000/01 for means).
- Significant differences in the variances and populations for 1998/99 and 1999/2000 and just for variances for 2000/01 between convex and composite banks (3032 v 11867 mm^2 for 1998/99, 920 v 6413 mm^2 for 1999/2000 and 2251 v 9916 mm^2 for 2000/01 for variances and 15 v 81 mm for 1998/99, -9 v 37 for 1999/2000 for means).

While these results clearly demonstrate that bank profile form has a significant effect on bank erosion during the wet season, most of the results are unexpected. The vertical bank class had a small sample size, which explains the lower erosion rates than for concave and composite banks. However, this is not a limitation of the other significant results. Concave banks exhibited greater erosion rates than both steeply sloping and convex banks. However, none of the basal less steep bank segments of the concave banks were well developed and hence would not have impacted on the cross-sectional flow velocity distribution. As a result, such poorly developed concave banks may maximise shear stress on the channel banks thus causing higher erosion rates.

Composite bank profiles exhibit greater erosion rates than vertical, steeply sloping and convex banks. Composite bank forms are common on Tributary Central, which exhibits the greatest erosion rates. Furthermore, this category has been used as a general class for a range of different bank forms (fig 5). Reclassification of the composite bank form into separate classes (fig 5) would be necessary to determine whether there are significant variations in erosion within this class.

In contrast to the above results, no significant differences ($\rho \leq 0.05$) in means/populations between different bank profile forms were recorded during the dry season for any of the three years. While some significant changes in variance were found, no clear trends were apparent and they are not discussed further here. Clearly the erosion pin data demonstrates that bank profile form exerts a significant control on bank erosion in the Ngarradj Creek catchment during the wet season. Similar results have been found elsewhere in Australia (Crouch 1987, Crouch & Blong 1989).

6.2 Planform effects on bank erosion

Planform effects on bank erosion should be greatest during the wet season when streamflow occurs. For a homogeneous river reach of constant discharge, the radius of curvature to channel width ratio (a dimensionless measure of bend curvature) is the most important control on lateral migration by bank erosion (Hickin & Nanson 1975, Nanson & Hickin 1983, Hickin & Nanson 1984, Nanson & Hickin 1986). Therefore, bank erosion during the wet season should be greatest on bends. Secondary currents combined with downstream flow vectors and flow separation should result in greater erosion rates on the outside bank of bends than on the inside or in straight reaches (Leopold & Wolman 1960, Hey & Thorne 1975, Thorne & Hey 1979, Bathurst et al 1977, 1979). Secondary currents are flows that occur in the plane normal to the local axis of the primary (ie downstream) flow and are commonly 10 to 20% of the magnitude of the primary flow velocity (Leopold et al 1960; Bathurst et al 1979). They combine with the primary downstream flow to produce a spiral helix or streamwise vortex called helicoidal flow (Leopold et al 1960; Hey & Thorne 1975; Thorne & Hey 1979). The three-dimensional flow pattern through bends without flow separation (see below) is outlined by Bathurst et al (1977; 1979), Hey and Thorne (1975) and Thorne and Hey (1979) and demonstrates that the greatest fluvial stress on the channel banks occurs downstream of the bend apex. The development of flow separation zones on the inside of bends is also important for causing bank erosion on the outside of the bend. Bagnold (1960) first recognised that flow along the inside bank of bends can become unstable and break away from the channel boundary, forming a flow separation envelope. Leeder & Bridges (1975) demonstrated that flow separation occurs when, for a given Froude Number, the radius of curvature to channel width ratio exceeds a critical value. When this occurs, the zone of active flow constricts around the bend due to the development of a flow separation envelope, often with a reverse current, on the inside of the bend, producing a zone of higher flow velocity and thus maximum bank erosion downstream of the bend apex at the outside bank (Leeder & Bridges 1975).

Insufficient data were obtained for channel constrictions for inclusion in the analyses. For the wet season, of the 30 statistical tests the following 12 results were significant at $\rho \leq 0.05$:

- Significant differences in the variances and populations for 2000/01 between the upstream limb of bends and bend apices (561 v 6821 mm^2 for variances; 0 v 41 mm for means).

- Significant differences in the variances and populations for 2000/01 between the upstream and downstream limb of bends (561 v 10776 mm^2 for variances; 0 v 62 mm for means).
- Significant differences in the variances and populations for 1998/99 and 2000/01 between bend apices and straight reaches (13033 v 3129 mm^2 for 1998/99 and 6821 v 1163 mm^2 for 2000/01 for variances; 96 v 18 mm for 1998/99 and 41 v 0 mm for 2000/01 for means).
- Significant differences in the variances and populations for 1999/2000 and 2000/01 between the downstream limb of bends and straight reaches (7333 v 1527 mm^2 for 1999/2000 and 10776 v 1163 mm^2 for 2000/01 for variances; 47 v 2 mm for 1999/2000 and 62 v 0 mm for 2000/01 for means).

These results demonstrate that the greatest erosion rates occur on the downstream limb of bends. For the significant results, the ranking of erosion rates in terms of magnitude is downstream limb of bends > bend apex > upstream limb of bends and straight reaches. This ranking conforms to what is known of the spatial distribution of fluvial stress on the channel boundary in curved channels, as outlined above.

In contrast to the above results, but as expected, no significant differences ($\rho \leq 0.05$) in means/populations between different channel planforms were recorded during the dry season for any of the three years. While some significant changes in variance were found, no clear trends were apparent and they are not discussed further here. Clearly the erosion pin data demonstrates that channel planform exerts a significant control on bank erosion in the Ngarradj catchment during the wet season.

7 Conclusions and recommendations

Up to three years of erosion pin measurements in the Ngarradj catchment have established that:

- Substantial bank erosion (up to 285 t/a) has occurred during the wet season on the mine site tributaries by rapid lateral migration (Tributary Central) and by erosion of gully sidewalls by a combination of within-gully flows and overland flow plunging over the sidewalls (Tributary North);
- Bank erosion also occurred during the dry season by desiccation and loss of cohesion of the sandy sediments, by faunal activity and by dry flow processes;
- Channels with dense riparian vegetation (the forested meandering reaches of Erskine et al 2001) did not generate significant amounts of sediment by bank erosion;
- As found elsewhere by others, deposition was also locally significant, despite the sandy bank sediments; and
- Bank profile form and channel planform exert a strong control on erosion rates during the wet but not during the dry season.

Saynor et al (2002a) clearly established that the lower gullied reach of Tributary North was initiated by erosion of a former track many years before the construction of the Jabiluka mine. Therefore, the high contemporary erosion rates are not related to mining activities. However, the chronological development of the meander loops in the sinuous reach of Tributary Central need to be documented by interpretation of all available vertical air photographs to determine the role, if any, that the mine played.

Bed scour was greater at the gauging stations than in the mine-site tributaries over the same time period that the erosion pin measurements were made (Saynor et al 2002b). Therefore, bed scour and consequent bank undermining are not significant causes of bank erosion in the Ngarradj catchment.

The present erosion pin program exhibited a number of minor shortcomings that should be redressed in future. Erosion pins were installed over two years (1998 and 1999) and only simple location diagrams were drawn to aid in pin recovery. No recovery pegs or base lines were installed near the top of the bank, as used by Wolman (1959), Hooke (1979) and Lawler (1993). This should be done in future. Nevertheless, the use of a metal detector generally resulted in the relocation of all pins. The data were also compromised by the installation of additional pins when complete burial had occurred. This caused confusion when the previously buried pin was re-exposed. Buried pins should not be replaced by additional pins. Stainless steel pins should be used in future to prevent rust-binding of sediments to pins. Greater attention also needs to be directed at establishing spatially representative measurement sites (Lawler 1993, Couper et al 2002). Erosion pins should not only be installed at or near cross sections nor on bends which are eroding. Instead, the full range of channelplan forms should be covered.

Most previous research on the use of pins to measure bank erosion was completed in environments with strongly coherent soil materials and steep to vertical river banks. The channels in the Ngarradj catchment are characterised by sandy sediments and are subjected to a markedly seasonal, tropical climate. Pins are not as effective in unvegetated sands as in silty or clayey bank sediments.

Erskine et al (2001) recommended that each sediment layer at the main erosion sites should be described according to the methodologies recommended by McDonald and Isbell (1990), bulk sampled and subjected to various laboratory tests to evaluate sediment erodibility. While many bank sediment descriptions have been completed (Erskine et al 2003), erodibility assessments have not. Erskine et al (1995) found that grain size analysis, the Emerson (1967) aggregate stability test and the pinhole dispersion test (Sherard et al 1976) were necessary to discriminate between stable and unstable bank materials. However, bank sediments are remarkably similar between sites (Erskine et al 2003), with the exception of site 6 on Tributary Central. Therefore, it is unlikely that differences in sediment characteristics are likely to be a significant explanatory variable in the measured bank erosion rates. It is recommended that the sediment erodibility assessments of bank materials proposed by Erskine et al (2001) should not be undertaken.

Negative pin values were commonly recorded, as found elsewhere in Australia and overseas (Saynor et al 1994, Erskine et al 1995, Couper et al 2002). This suggests that bank erosion is an episodic process that is not characterised by quasi-continuous bank retreat. Much greater emphasis should be directed at representative sampling of bank erosion for the construction of the sediment budget. Sample sites do not have to be restricted to permanently marked cross sections but should representatively cover the full range of bank conditions throughout the channel network.

It is recommended that:

- The erosion pin program in the Ngarradj catchment should be reduced by concentrating solely on the mine site tributaries.

- The erosion pin program should cease at the upper Swift Creek and East Tributary gauging station sites due to the stable channel boundary. The forested banks and high large woody debris loading contribute to this stability.
- Pins are not effective at the Swift Creek gauging station because of the sandy, gently sloping banks. The current program should be terminated.
- Pins are not needed at the cross sections on Tributary Central where rapid lateral migration is occurring and permanently marked cross sections have been installed (TC06, TC07, TC11).
- A recovery peg and/or base line should be installed at the top of the bank to aid in pin recovery.
- Stainless steel pins should be used to stop rusting, a problem also identified by Bridges and Harding (1971) and Lawler (1993). Rusted pins cause the binding of sediment to the pin and cause problems with pin measurement.
- Pins should never be replaced when they have been buried.
- Erosion pin sample sites should representatively cover the full range of channel planforms, bank types and sediment textures to enable meaningful spatial extrapolation of the results.
- The reduced but improved erosion pin program should be implemented.

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