Cross-sectional and

scour and fill changes in

the Ngarradj catchment

between 1998 and 2003

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Australian Government

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Executive summary

To measure large-scale bank erosion in the Ngarradj catchment, in which the Jabiluka mine is located, 56 permanently marked channel cross sections were installed in 1998 on the mine site tributaries (Tributaries North and Central) and at the three Environmental Research Institute of the Supervising Scientist (*eriss*) gauging stations. The sections have been resurveyed annually during the dry season and the results to 2003 are analysed in this report. To measure scour and fill of the sand-bed streams, 30 scour chains were used at some of the above cross sections. They were installed progressively during the 1998 and 1999 dry seasons and have been measured annually during successive dry seasons. The results to 2003 are also analysed in this report. The period between 1998 and 2003 was characterised by average to above average rainfall.

The cross section results indicated that:

- There were minor changes in the Floodout Reach of Tributary North which had developed before the Jabiluka mine headworks and infrastructure had been constructed.
- The main gully on Tributary North was also initiated before the Jabiluka mine was constructed and is currently developing by nickpoint migration at a rate of 1.56 m/a (metres per annum), gully widening and bed degradation.
- The tributary gully on Tributary North was initiated by erosion of a former track between 1984 and 1987, and is currently developing by gully widening and bed aggradation.
- Tributary Central is currently eroding by a combination of active lateral migration, bed degradation and channel widening and these geomorphic processes were initiated before the construction of the Jabiluka mine.
- Minor changes (< 10%) in all hydraulic geometry parameters occurred at all sections at the East Tributary gauge, except the one at the gauging station, which is continuously disturbed by gauging activities.
- Sand storage is currently occurring in the upper Swift Creek gauge reach with all sections exhibiting a decrease in area and in mean and maximum depth.
- Sand storage also dominated at the Swift Creek gauge although it was not as great as at the upper Swift Creek gauge.

The influence of mean bankfull flow velocity, discharge and specific stream power between 1998 and 2003 on percentage change in bankfull channel geometry parameters over the same period in each study reach was assessed by determining product moment correlation coefficients between these two variables. It was found that:

- There were no significant correlations for the Tributary North main gully and for the upper Swift Creek gauge.
- Percentage change in area, width and maximum depth was significantly correlated with mean bankfull flow velocity and specific stream power on the Tributary North tributary gully. The first two were negatively and the last one positively correlated. The reason for the inverse relationship between percentage change in area and width, and the hydraulic parameters is that unstable sites were those with the smallest area and width that were undergoing active enlargement and widening near the primary nickpoint whereas enlarged cross sections further downstream were more stable. The positive correlation between percentage change in maximum depth and mean bankfull flow velocity and

specific stream power indicated that the greatest thalweg scour occurred at sites of greatest hydraulic stress.

- There was only one significant correlation (percentage change in area and mean bankfull discharge) on Tributary Central because the greatest channel changes were caused by lateral migration and hence any hydraulic control on channel changes was masked by planform influences.
- While there were many significant correlations at the East Tributary gauge, extreme values at both tails of the data unduly influenced the significance of the relationships.
- At the Swift Creek gauge percentage change in maximum depth was positively related to mean bankfull flow velocity and specific stream power. Thalweg scour was closely related to hydraulic stress.

The survey data were also used to calculate changes in sediment storage for each measurement reach for each wet season between 1998 and 2003 as well as for the complete period. The channel network was a net sediment source due mainly to high rates of channel erosion in Tributary Central. However, the sediment generated by channel erosion on Tributary Central is not supplied to the main channel of Ngarradj but is stored in the channel and fan of Tributary Central and the anabranch of Ngarradj. When the results for Tributary Central are removed from the catchment estimates, sediment storage dominates. Each measurement reach alternated between a sediment source and a sediment store over time although the trends were not synchronous between reaches.

Average annual scour and fill in each measurement reach for each wet season usually overlap with each other, allowing for plus or minus twice the standard error of estimate of the mean. This indicates that mean annual scour and fill are not significantly different between years. Nevertheless, there were substantial variations between wet seasons with the mean annual scour and fill in the measurement reaches varying from -3 ± 24 mm (scour) to 142 ± 41 mm (fill). Net fill is currently occurring in the Ngarradj catchment and hence the bed is a sand storage. However, the current data are not sufficiently reliable to preclude net scour. Furthermore, net scour was recorded in at least one measurement reach for all years, except the first when less data were available.

Continued annual monitoring of the cross sections and scour chains is recommended while the Jabiluka mine is under long-term care and maintenance so as to provide data against which subsequent mine impacts or the success of mine rehabilitation can be determined.

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Cross-sectional and scour and fill changes in the Ngarradj catchment between 1998 and 2003

MJ Saynor, WD Erskine & KG Evans

1 Introduction

Erskine et al (2001) proposed that a sediment budget framework should be adopted by the Environmental Research Institute of the Supervising Scientist (*eriss*) to assess the physical impacts, if any, of the Jabiluka mine on the Ngarradj catchment (fig 1). Various fluvial erosion processes were identified during initial field inspections before construction of the Jabiluka mine had commenced (Erskine et al 2001). Two of these processes were bank erosion and scour and fill of the sandy creek beds. To measure the amount of large-scale bank erosion, permanently marked channel cross sections on the mine site tributaries (Tributaries North and Central) and at the three *eriss* gauging stations (Moliere et al 2002) (fig1) were installed. To measure scour and fill, and hence the annual depth of reworking of the river beds, scour chains were used at some of the above cross sections (Saynor 2000, Erskine et al 2001, Saynor et al 2002b).

Erosion pins were used to measure small-scale and slow rates of bank erosion in the Ngarradj catchment. Saynor et al (2003) reported the results of the erosion pin measurements. They found that, during a period of above average rainfall (1998-2001):

- 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 on the mine site tributaries during the dry season by desiccation and consequent loss of cohesion of the sandy sediments, by faunal activity and by dry flow processes.
- Channels with dense riparian vegetation (the Forested Meandering and Sinuous Reaches of Erskine et al (2001)) characterise the three *eriss* gauging station reaches (East Tributary, upper Swift Creek and Swift Creek gauges) and did not generate significant amounts of sediment by bank erosion.
- Deposition (ie negative erosion pin values were commonly recorded at all sites) was also locally significant, despite the sandy bank sediments. This indicates that small-scale bank erosion is an episodic process that is not characterised by quasi-continuous bank retreat.
- Bank profile form and channel planform exerted a strong control on erosion rates during the wet but not during the dry season.

Saynor et al (2004a) found that repeated vehicle passes over burnt grass swales on the Jabiluka Mineral Lease increased soil bulk density and locally disrupted the surficial root and algal mats, lowering the critical sheer stress for sediment transport. Overland flow during the wet season eroded initial discontinuous, flow-aligned scour holes in the wheel ruts which developed into a gully in one case but which reverted back to a grass swale in another, when traffic bypassed the eroded section, allowing grass to re-establish.

In October 1996 Energy Resources of Australia submitted an environmental impact statement for the mining of uranium at Jabiluka in the Kakadu region (fig 1). While the Australian Minister for Environment and Heritage approved this initial proposal in October 1997 subject to 75 conditions, an alternative development was subsequently prepared and approved in August 1998, subject to another 15 conditions (Johnston & Prendergast 1999). The Jabiluka Mineral Lease (fig 1) is surrounded on three sides by Kakadu National Park and by the Ranger Mining Lease on the fourth. The Magela Creek wetlands of Kakadu National Park are recognised under the Ramsar Convention on Wetlands of International Importance (Finlayson & von Oertzen 1996; Kakadu Board of Management & Parks Australia 1999). Ngarradj flows into the Magela Creek floodplain and wetlands (fig1). During the 1998 dry season, the portal, retention pond and other head works were constructed and mineralised and non-mineralised ore stockpiles were created from the material excavated from the decline and ore body. An area of about 19 ha was disturbed by mining activities. Development work at Jabiluka ceased in September 1999 after which the site entered an environmental management and standby phase with no mining (Supervising Scientist 2000), which continued until 2003. The mine is now under long-term care and maintenance following the backfill of the decline with mineralised stockpile material and non-mineralised waste rock, the sealing of the decline to prevent water entry, and the removal of non-essential infrastructure during the 2003 dry season.

The aims of the present work are:

- To outline the research design to determine channel changes and scour and fill in the channels on the Jabiluka Mineral Lease.
- To document the cross section and scour chain program in the Ngarradj catchment.
- To analyse the cross section and scour chain results between 1998 and 2003.
- To review future requirements of these programs.

2 Research design

The basis of the *eriss* programs in the Ngarradj catchment is a comparison of channel change and scour and fill between mine-impacted and non-mine-impacted sites (Erskine et al 2001). A multiple after-control-impact study with sampling spatially and temporally replicated at control and impact locations was implemented (Gladstone & Schreider 2003). Tributary North and Tributary Central are the pathways for water, sediments and solutes to enter Ngarradj from the Jabiluka mine site (fig 1). East Tributary and upper Swift Creek gauges are located in river reaches that are not impacted by the mine (fig 1) and serve as multiple controls. The Swift Creek gauge is located in a reach of Ngarradj immediately below the junction of the mine site tributaries with Ngarradj (fig 1) and hence potentially serves as a measure of mine impacts on the larger Ngarradj channel. It was not possible to use a standard or modified BACI (Before After Control Impact) design because no pre-mining work was possible before mid-1998. Nevertheless, all work reported below was initiated before there had been any runoff from the Jabiluka mine at the beginning of the 1998/1999 wet season.



Figure 1 The Ngarradj catchment showing the Jabiluka Mineral Lease, *eriss*'s gauging stations and local creek names. SC refers to Swift Creek gauging station, TN Tributary North, ET East Tributary gauging station, TC Tributary Central, TS Tributary South, TW Tributary West and UM upper Swift Creek gauging station.

3 Methods

Fifty-six permanently monumented channel cross sections were installed, following the approach of Miller and Leopold (1963) and Leopold et al (1966), to measure large-scale erosion and/or deposition that can be detected by standard surveying techniques (Erskine et al 2001). This method was adopted as part of the Vigil Network, the USA's contribution to the International Hydrological Decade (Leopold 1962, Emmett 1965; Leopold & Emmett 1965, Emmett & Hadley 1968). Multiple cross sections were installed at each *eriss* gauging station (upper Swift Creek, Swift Creek and East Tributary) as well as on the mine site tributaries, Tributary North and Tributary Central (fig 1). Site-specific details are provided below. Repeated surveys of permanently marked cross sections only measure the net change between successive wet seasons. The actual depths of scour and fill during floods are usually much greater (Emmett & Leopold 1963, Leopold et al 1966). The channel bed is the first temporary sediment storage for any sandy material and possible associated contaminants delivered from the mine to the channel network. Therefore, scour chains were used at some of the above cross sections to determine scour and fill during each wet season so as to assess to what depth in the channel bed, sediment generated on the mine site may be stored.

3.1 Channel cross sections

The permanently marked cross sections were installed during the 1998 dry season and have been surveyed annually during each subsequent dry season to 2003 to determine the net change during each intervening wet season. The cross sections were marked using a star picket driven into the ground with the top 0.3 m encased with a circular concrete collar (plinth) at each end of the cross section. A coach bolt was set into the concrete (with a small drill hole in the top) to provide an accurate bench mark. Full details of the cross section markers and bench marks are listed in Saynor et al (2001). Cross sections were surveyed using a Topcon Total Station. The cross sections were used to determine bankfull hydraulic geometry for each survey and changes in channel geometry between surveys.

The number of cross sections in each study reach is listed in table 1. The two mine site tributaries (Tributary North and Tributary Central) were sampled for the complete channel distance between the mine site and the junction with Ngarradj (Tributary North) or its anabranch (Tributary Central). Ngarradj downstream of the junction with Tributary North and the anabranch was sampled in a reach centred on the *eriss* Swift Creek gauge. The two control sites were also located at *eriss* gauging stations, East Tributary and upper Swift Creek (table 1). While the *eriss* gauging station reaches were relatively short (table 1), the availability of discharge records was necessary for checking some methods and results, as outlined in subsequent sections.

Study Reach	Number of Cross Sections	Length of Channel Sampled (Channel Widths)	Average Spacing between Cross Sections (Channel Widths)
Tributary North	17	85	5.0
Tributary Central	15	82	5.5
East Tributary Gauge	8	7.6	0.9
Upper Swift Creek Gauge	8	10	1.3
Swift Creek Gauge	8	9.0	1.1
Total	56	N/A	N/A

 Table 1
 Number of cross sections installed in the Ngarradj catchment

3.2 Hydraulic geometry

Bankfull stage (the channel-floodplain junction) was initially determined at each cross section using Wolman's (1955) objective method of the point corresponding to the minimum widthdepth ratio. This was done for any section where bankfull stage was difficult to determine visually. As more experience was gained with local conditions, it was possible to determine bankfull stage from field knowledge (Williams 1978). The lowest inflection point of the bank profile was adopted as bankfull stage.

Mean flow velocity at bankfull stage was calculated by Manning's equation:

$$u = n^{-1} . R^{0.67} . S^{0.5}$$
 (1)

where u is mean flow velocity (m/s), n is Manning's roughness coefficient, R is bankfull hydraulic radius (m) and S is energy slope (m/m). A reach-averaged Manning's n value was initially determined by Cowan's (1956) method and by comparison of channel conditions with those for which roughness coefficients have been determined (Barnes 1967, Arcement & Schneider 1984). The estimated Manning's n values were then checked against those derived from the highest within-channel velocity-area gaugings at the three *eriss* gauging stations. These gaugings were completed at discharges approaching bankfull stage. Hydraulic radius was calculated from the cross sections as:

$$\mathbf{R} = \mathbf{A} / \mathbf{P} \tag{2}$$

where A is cross-sectional area (m^2) and P is wetted perimeter (m). However, hydraulic mean depth (R_d) was substituted for hydraulic radius in Manning's equation and was calculated from the cross sections as:

$$\mathbf{R}_{d} = \mathbf{A} / \mathbf{W} \tag{3}$$

where W is bankfull channel width (m). Bed slope or the water surface slope for a specific flood was surveyed at each site and used instead of energy slope.

Bankfull discharge (Q in m³/s) was calculated as:

$$\mathbf{Q} = \mathbf{u}.\mathbf{A} \tag{4}$$

Specific stream power (ω in W/m²) at bankfull stage was calculated by:

$$\omega = \rho.g.Q.S/W \tag{5}$$

where ρ is fluid density (g/cm³) and g is the gravitational acceleration constant (9.8 m/s²).

The cross-sectional data were checked against those derived from velocity-area gaugings at the gauging wire at the three *eriss* gauging stations.

3.3 Scour chains

Depths of scour and fill can be measured by scour chains, as described by Emmett and Leopold (1963) and Emmett (1965). Scour chains were installed in various reaches of the Ngarradj catchment so that the top link of the chain was level with the channel bed (table 2). After each wet season the elevation of the stream bed was resurveyed and the bed was excavated until the chain was exposed. If scour had occurred, a part of the chain was lying horizontally (figs 2 & 3). The difference between the existing bed elevation and the horizontal chain was the depth of fill (fig 3). If no scour had occurred, the amount of fill was the depth of sediment above the top of the buried chain. If the amount of fill equalled scour, there was no net change in bed level between years although scour and fill had occurred (fig 4).

Scour chains were installed during the late dry seasons of 1998 and 1999. Table 2 contains information on the number and timing of scour chain installation in each reach. The scour chains were always located on a surveyed cross section (table 2) and Saynor et al (2001) document precise details of their location. Only three scour chains were used on Tributary Central because bedrock, pebbles and/or clay usually prevented bed excavation for the installation of chains and clearly restricted the amount of flood scour.

Location	No. of cross sections with scour chains	Year of initial installation	Total number of scour chains in each reach	
Swift Creek gauge	3	1998 and 1999	9	
East Tributary gauge	4	1998	5	
Upper Swift Creek gauge	3	1998	6	
Tributary North	6	1999	7	
Tributary Central	3	1998 and 1999	3	
Total	20	1998 and 1999	30	

 Table 2
 Number of scour chains installed in each study reach in the Ngarradj catchment



Figure 2 Scour chain orientated downstream at TN02 on 24 October 2000. Arrow indicates flow direction.



Figure 3 Diagrammatic representation of the full range of scour chain behaviour when there was net scour depicted by the middle example in figure 4. Net fill is shown by the top example in figure 4 and no change, by the lower example in figure 4.

Late in each dry season when the water table was at its lowest, the scour chains were relocated using the diagrams and measurements in Saynor et al (2001) and, more importantly, a metal detector. Measurements of the depth to the scour chain and the bed surface level were then obtained. A wooden board was positioned over the upstream face of the excavation and all measurements were taken to the bottom of this board which equated to the then bed level. A photograph was taken to show the position of the chain and the direction of flow was indicated by an arrow marked on paper or by a trowel, pen or ruler pointing downstream (fig 2). As the scoured part of the chain was not always lying horizontal, two measurements were taken to determine the scour depth (fig 3):

- depth to top of first link.
- depth to the first vertical link.

After these measurements were made the chain was carefully straightened vertically and then the depth to the top of the straightened chain from the base of the wooden board was measured.

All measurements were made as positive values except when the straightened chain was higher then the current bed level when the value was assigned a negative value. These measurements are used to determine scour and fill and are explained in the next section. Once all the measurements had been made, the chain was reset so that the top link was level with the channel bed.



Figure 4 Three examples of net channel bed change during the wet season measured by scour chains. Net fill occurs when the bed level for the 2nd year is higher than for the 1st (top). Net scour occurs when the bed level for the 2nd year is lower than for the 1st (middle). No net change occurs when the bed level for the 1st and 2nd years is the same (bottom).

3.4 Scour and fill calculations

The top of the highest link of each chain is the zero datum for the next wet season. The values are all made to this datum even though some of the measurements are made to the bed level for year 2 (fig 4). Once the scour chains are reset the datum is then also reset and the bed level is called Year 1 for the following year (fig 4).

Maximum scour (S_M) is determined as

$$S_{\rm M} = F_{\rm M} - \rm{DSC}$$
(6)

where F_M is the maximum amount of fill during a wet season and DSC is the vertical distance from the year 2 bed level to the top of the straightened chain. It is essential that the mathematical signs in figure 4 are used.

A positive value of DSC indicates net fill from year 1 to year 2 and a negative value, net scour (fig 4). This convention of positive values for fill and negative values for scour has been used by, among others, Emmett (1965), Leopold et al (1966), Roberts (1991), Fowler and Wilson (1995) and Locher (1997). Figure 4 shows the three possible situations, net fill, net scour and no net change.

4 Study area and catchment hydrology

The purpose of this section is to briefly outline the study area characteristics and hydrology during the measurement period. Steep sandstone slopes with lower scarps form the Jabiluka outlier on the western side of the Ngarradj catchment around the mine site (fig 1). This is an eroded remnant of the Arnhem Land plateau which is more extensively developed on the eastern side of the valley (Erskine et al 2001). Long colluvial footslopes and fans have accumulated between the sandstone outcrops and contemporary floodplains (Erskine et al 2001). Near the escarpment, Roberts (1991) found that sand fans in this area began to accumulate at 230–220 and 120–100 ka, which coincide with the start of the penultimate and last interglacials respectively. The extensive undulating lowlands in the Ngarradj catchment are part of the lateritised Koolpinyah Surface of Hays (1967), which has an age range from Proterozoic to Pleistocene (Erskine & Saynor 2000).

The Jabiluka outlier and Arnhem Land plateau are composed of resistant, horizontally bedded, vertically jointed, strongly ferruginous, medium quartz sandstone of the Palaeoproterozoic (Statherian) Mamadawerre Sandstone of the Kombolgie Subgroup (Needham 1988, Carson et al 1999). The sandstone is generally more than 95% medium to coarse grained, moderately well sorted, subrounded to subangular quartz grains with minor lithic fragments of quartzite and quartz-feldspar granophyric intergrowths (Needham 1988).

Wells (1979) mapped the soils of 38 km² of the Jabiluka Mineral Lease. The area surrounding the Jabiluka mine site exhibits very shallow sands on steep sandstone slopes, shallow red or brown uniform sands at the base of bedrock outcrops and deep uniform sands on the footslopes. The regolith of the footslopes and fans is comprised largely of quartz sand and overlies deeply weathered lateritic saprolites (Bettenay et al 1981). Lateritic pallid zones are dominated by kaolinite in the clay fraction while the yellow and red sandy clays and mottled zones are largely kaolinite with some haematite and/or goethite (Bettanay et al 1981).

Cross sections and scour chains were installed at the three *eriss* gauging stations (fig 1). The catchment areas at the upper Swift Creek, Swift Creek and East Tributary gauges are 18.8, 43.6 and 8.5 km² respectively. Cross sections and scour chains were also installed on the mine site tributaries (Tributary North and Tributary Central). The total catchment areas of Tributary

North and Tributary Central are 0.6 and 2.5 km² respectively. The bed sediments in the Ngarradj catchment have been described by Erskine et al (2003), using Folk's (1954, 1974) textural classification scheme, at every scour chain site. The texture groups for each study site are outlined in section 5.

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, 2003). 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 cross section and scour chain measurements was recorded on 13 September (2002) and the latest rainfall was recorded on 24 May (2000) (table 3). Cross section and scour chain measurements were conducted between late 1998 and 2003 when rainfall was at or above average (table 3). Moliere et al (2002, 2003) estimated that the average recurrence intervals for annual rainfall for the 1998/1999, 1999/2000, 2000/2001, 2001/2002 and 2002/2003 water years were 13, 71, 21, 2 and 9 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 (table 3). The amount of rainfall before streamflow commenced varied between 250 and 440 mm (table 3). Streamflow persisted until between April and July each year (Moliere et al 2002, 2003). The largest peak instantaneous discharges were recorded during the 1998/1999 wet season but the variation between years was minor (table 3).

Bankfull discharge occurred at least once during each wet season (Moliere et al 2002, 2003). During the dry season, all channels ceased flowing and the water table dropped to at least 0.5 m below the river bed (Saynor et al 2002b).

Year	Total rainfall (mm) [ARI (y)]	Rainfall period	Station	Antecedent rainfall (mm)	Runoff period	Total runoff (ML) [Peak discharge (m³s⁻¹)]
1998/99	1826 [13]	20 Sep – 28 Apr	SC	430(1)	9 Dec – 27 May	33665 [22.3]
			UM	440 ⁽¹⁾	12 Dec – 10 Jun	15666 [15.0]
			ET	415 ⁽¹⁾	9 Dec – 27 May	7621 [8.5]
1999/00	2047 [71]	14 Oct – 24 May	SC	260	20 Nov – 14 Jul	34899 [18.1]
			UM	305	20 Nov – 20 Jul	17426 [12.2]
			ET	280	20 Nov ⁽²⁾ – 25 Jun	8532 [8.1]
2000/01	1897 [21]	14 Oct – 27 Apr	SC	250	29 Nov – 14 Jun	34781 [20.6]
			UM	250	3 Dec – 14 Jun	17052 [13.0]
			ET	245	28 Nov – 21 May	8275 [8.2]
2001/02	1390 [2]	17 Oct – 14 Apr	SC	420	31 Dec – 15 Apr	14382 [22.0]
			UM	370	31 Dec – 1 May	7495 [13.6]
			ET	330	28 Dec – 25 Apr	3963 [8.3]
2002/03	1769 [9]	13 Sep – 1 May	SC	225	22 Dec – 7 May	33245 [21.2]
			UM	250	20 Dec – 1 Jun	18101 ⁽³⁾ [12.9]
			ET	355	1 Jan – 7 May	7249 [8.2]

Table 3	Total rainfall over	r the Ngarrad	catchment and	d runoff at e	each gauging	station for	the 5-year
monitorir	ng period (1998 t	o 2003). Data	sourced from M	/loliere et a	al (2002, 2003	5).	

(1) Data partly provided by Energy Resources of Australia; (2) A small surge of runoff occurred on 8 Nov, 1900–2300 h (Moliere et al 2002, Appendix A); (3) Total runoff partly infilled using predicted discharge data generated from the HEC-HMS model (section 2.2.1)

5 Annual cross section surveys – results and discussion

The data for the annual cross section surveys in the Ngarradj catchment between 1998 and 2001 are presented in Saynor et al (2002a) and those for 2002 and 2003 in Saynor et al (2004b). The cross section plots for each study reach are shown in Appendices A to E. Values for the various hydraulic geometry parameters are included in tables for each study reach in the sections below. Where changes in hydraulic geometry parameters between 1998 and 2003 are less than $\pm 1\%$, the section is called stable.

5.1 Tributary North

A total of 17 cross sections was installed (fig 5) downstream of the Jabiluka mine in the Floodout and Gullied Reaches of Erskine et al (2001). Four cross sections (TN10, TN11, TN12 & TN13) of the Floodout Reach (fig 6) are presented in Appendix A but no hydraulic geometry parameters have been calculated because there were multiple poorly defined channels. Bankfull stage has no relevance to these channels in a floodout zone where sand deposition is active and channels are decaying. Eight cross sections are located across the downstream main gully (fig 5 & 7). A tributary gully joins Tributary North on the left bank approximately 30 m upstream of the confluence with Ngarradj. Five cross sections were surveyed across the tributary gully (fig 5). Both the main and tributary gullies are incised and have never been observed to flow overbank during the study period, unlike those at the three *eriss* gauging stations. Therefore, the bankfull channel is not flanked by a floodplain and the frequency of bankfull discharge decreases greatly between the Floodout and Gullied Reaches. In both the main and tributary gully of Tributary North, bed sediments to a depth of 1.5 m are dominated by slightly granular fine-coarse sand (Erskine et al 2003), according to Folk's (1954, 1974) textural classification scheme.

The cross sections are shown from upstream to downstream in Appendix A and the location of the cross sections is shown in figure 5. Several cross sections extend across both the main and tributary gullies (fig 5). The results are presented for the Floodout Reach, the main gully and the tributary gully in the following subsections.

For the determination of the values of the hydraulic geometry parameters in tables 4 and 5, the slope used was 0.00412 m/m (4.12 m/km) which was determined from a longitudinal bed survey using differential GPS during the 1998 dry season. The Manning's n value used was 0.04. No velocity-area gaugings were undertaken on Tributary North to check the accuracy of the estimated roughness coefficients. However, where velocity-area gauging data are available at the *eriss* stations, close correspondence between estimated and measured values was found (see below). All comparisons for the hydraulic geometry parameters are made with the first survey which was completed in 1998.

5.1.1 Tributary North floodout reach

The four cross sections of the Floodout Reach exhibit small channels located in a drainage depression. Only minor, localised erosion and deposition have occurred between 1998 and 2003 (Appendix A). Air photographs show that the floodout had developed by 1964, long before construction of the Jabiluka mine in 1998. The floodout represented a zone where the channel dissipated in a series of grassed swales below the footslope of the sandstone outlier. A small gully developed at cross sections TN11 and TN12 by erosion of a former track (fig 5) when vehicles disrupted the grass root mat (Saynor et al 2004a). This gully was initiated after 1975 and the eroded sediments have been deposited as a splay at cross section TN10 (Appendix A).

5.1.2 Tributary North main gully

The cross-sectional area at cross section TN01, the closest section to the primary nickpoint at the upstream end of the Gullied Reach (Erskine et al 2001) (fig 8), increased by 20% from 1998 to 1999 by nickpoint retreat and subsequent erosion. The 2003 survey compared to the 1998 survey shows only a 16% increase in area, indicating that there has been deposition as the nickpoint migrated further upstream after 1999 (see below). Of the remaining seven cross sections, three increased in area by up to 14%, three decreased in area by up to 3%, and one was stable between 1998 and 2003. For the complete eight cross sections, the changes recorded between 1998 and 2003 included:

- Width increased at seven sections by up to 21% and was stable at one section.
- Mean depth decreased at six sections by up to 6% and increased at two sections by up to 8%.
- Maximum depth increased at seven sections by up to 31% and was stable at one section.
- Mean velocity decreased at five sections by up to 2.8%, increased at two sections by up to 4.7% and was stable at one section.
- Bankfull discharge decreased at four sections by up to 5.3% and increased at four sections by up to 16%.
- Specific stream power decreased at six sections by up to 7% and increased at two sections by up to 11%.

The above hydraulic changes overestimate the magnitude of actual changes because bankfull discharge has not been recorded during the study period. Wet season flood discharges have not exceeded a stage of 1 m and the frequency of bankfull discharge in incised channels is usually a very rare occurrence, if it ever occurs.

In comparison to the incised channels discussed in Darby and Simon (1999), the Gullied Reach of Tributary North is developing by the upstream migration of the primary nickpoint, and subsequent gully widening and bed degradation. The upstream limit of the main gully has been surveyed each year between 1998 and 2003, during which time the nickpoint has migrated upstream by 7.8 m (fig 8). Nickpoint migration and subsequent gully widening were occurring before the development of the Jabiluka mine and their rates of activity have not been accelerated, as outlined below.

Stereoscopic interpretation of all vertical air photographs of Tributary North which were flown at a scale greater than 1:50 000 revealed that:

- There was no gully on Tributary North in 1950, only a series of grassed swales in a broad drainage depression.
- The Floodout Reach with its sand deposits was present in 1964.
- A track ('old track' in fig 5) in the general area of Tributary North had been formed by 1975.
- The main gully on the lower section of Tributary North was initiated at the junction with Ngarradj between 1975 and 1981, and eroded about 100 m upstream of Ngarradj over this time period.
- This gully had eroded about a further 200 m upstream by 1984.
- The downstream section of the 'old track' (fig 5) had gullied by 1987 forming the tributary gully.



Figure 5 Location of the permanently marked cross sections and river reaches of Erskine et al (2001) on Tributary North

Therefore, it is clear that the Jabiluka mine was developed after the formation of the Floodout and Gullied Reaches of Erskine et al (2001) on Tributary North. The nickpoint migration rate between 1975 and 1984 was about 30.0 m/a but had decreased to 1.56 m/a between 1998 and 2003.



Figure 6 Floodout Reach of Tributary North showing flowing water in wheel ruts of the old track at cross sections TN11 and TN12, and splay at cross section TN10



Figure 7 Main gully of Tributary North at cross section TN03



Figure 8 Annual surveys of the primary nickpoint at the head of Erskine et al's (2001) gullied reach on the main gully of Tributary North

5.1.3 Tributary North tributary gully

The tributary gully was initiated by erosion of the 'old track' (fig 5) between 1984 and 1987 (Saynor et al 2004a), and is still actively developing. The tributary gully is located on a surface about 0.3 m higher than the swale which has been eroded by the main gully (Appendix A). This higher surface would not have gullied if the stabilising root mat had not been breached by multiple vehicle passes along the old track (Saynor et al 2004a).

For the five cross sections of the tributary gully, the changes recorded between 1998 and 2003 included:

- Cross-sectional area decreased at two sections by up to 5% and was stable at three sections.
- Width increased at four sections by up to 20% and decreased at the other by 3%.
- Mean depth decreased at all five sections by up to 15%.
- Maximum depth decreased at four sections by up to 10% and was stable at the other.
- Mean velocity decreased at all five sections by up to 12%.
- Bankfull discharge decreased at all five sections by up to 11%.
- Specific stream power decreased at all five sections by up to 25%.

The hydraulic changes were caused by aggradation. However, the comments in the previous subsection about the frequency of bankfull discharge in incised channels are also relevant here. Cross section TN08 recorded the greatest increase in width as well as the greatest decrease in both mean and maximum depth. The sediment eroded from the banks by widening has been temporarily stored in the bed, resulting in no net change in area at this section. The changes in width, mean and maximum depth indicate that most sections are exhibiting similar trends.

Bankfull Hydraulic Geometry Parameters			TN	101		TN02							
	1998	1999	2000	2001	2002	2003		1988	1999	2000	2001	2002	
Area (m²)	2.10	2.52	2.48	2.48	2.52	2.44		2.99	2.99	2.98	3.04	3.03	
Width (m)	3.81	4.11	4.45	4.41	4.57	4.62		6.54	6.48	6.45	6.51	6.53	
Hydraulic mean depth (m)	0.55	0.61	0.56	0.56	0.55	0.53		0.46	0.46	0.46	0.47	0.46	
Maximum depth (m)	0.913	1.021	0.955	0.982	0.961	0.977		1.009	1.051	1.116	1.154	1.108	
Mean velocity (ms ⁻¹)	1.08	1.16	1.09	1.09	1.08	1.05		0.95	0.96	0.96	0.96	0.96	
Discharge Q (m ³ s ⁻¹)	2.26	2.91	2.69	2.71	2.71	2.55		2.85	2.87	2.86	2.93	2.91	
Specific Stream Power (Wm ⁻²)	23.9	28.5	24.4	24.8	23.9	22.24		17.5	17.8	17.9	18.2	18.0	

 Table 4
 Bankfull hydraulic geometry parameter values for Tributary North main gully 1998–2003. For location of cross sections see fig 5.

Bankfull Hydraulic Geometry			TN	103					TN	104		
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003
Area (m ²)	3.14	3.13	3.01	3.20	3.05	3.13	1.25	1.39	1.33	1.35	1.43	1.43
Width (m)	5.00	4.99	5.05	5.11	5.06	5.16	4.01	3.64	3.51	3.63	4.26	4.47
Hydraulic mean depth (m)	0.63	0.63	0.60	0.63	0.60	0.61	0.31	0.38	0.38	0.37	0.34	0.32
Maximum depth (m)	1.095	1.216	1.111	1.257	1.190	1.202	0.644	0.774	0.723	0.750	0.867	0.832
Mean velocity (ms-1)	1.18	1.18	1.14	1.17	1.14	1.15	0.74	0.84	0.84	0.83	0.78	0.75
Discharge Q (m ³ s ⁻¹)	3.70	3.68	3.43	3.76	3.49	3.60	0.92	1.17	1.12	1.12	1.11	1.07
Specific Stream Power (Wm ⁻²)	29.8	29.7	27.4	29.7	27.8	28.2	9.2	13.0	12.9	12.4	10.6	9.7

Bankfull Hydraulic Geometry Parameters			TN	106			TN07							
Parameters	1998	1999	2000	2001	2002	2003		1998	1999	2000	2001	2002		
Area (m ²)	2.10	2.29	2.22	2.17	2.20	2.23		2.25	2.30	2.27	2.26	2.26		
Width (m)	5.32	5.43	5.40	5.30	5.34	5.32		5.36	5.42	5.35	5.18	5.36		
Hydraulic mean depth (m)	0.39	0.42	0.41	0.41	0.41	0.42		0.42	0.42	0.42	0.44	0.42		
Maximum depth (m)	0.661	0.750	0.761	0.729	0.905	0.866		0.776	0.798	0.862	0.852	0.872	(
Mean velocity (ms ⁻¹)	0.86	0.90	0.88	0.88	0.89	0.90		0.90	0.91	0.91	0.92	0.90		
Discharge Q (m ³ s ⁻¹)	1.81	2.07	1.96	1.92	1.95	2.00		2.03	2.08	2.06	2.08	2.04		
Specific Stream Power (Wm-2)	13.7	15.4	14.6	14.6	14.7	15.2		15.3	15.5	15.5	16.2	15.3		

 Table 4 Cont.
 Bankfull hydraulic geometry parameter values for Tributary North main gully 1998–2003. For location of cross sections see fig 5.

Bankfull Hydraulic Geometry			TN	108			TN09							
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003		
Area (m ²)	5.28	5.12	5.10	4.98	5.01	5.16	6.98	7.04	6.96	6.91	6.96	6.92		
Width (m)	9.85	9.72	9.80	9.74	9.60	10.03	9.86	9.78	9.96	9.95	10.00	9.91		
Hydraulic mean depth (m)	0.54	0.53	0.52	0.51	0.52	0.51	0.71	0.72	0.70	0.69	0.70	0.70		
Maximum depth (m)	0.965	1.053	1.022	1.011	1.020	0.998	1.069	1.097	1.097	1.095	1.083	1.094		
Mean velocity (ms ⁻¹)	1.06	1.05	1.04	1.03	1.04	1.03	1.27	1.29	1.26	1.26	1.26	1.26		
Discharge Q (m ³ s ⁻¹)	5.59	5.36	5.30	5.10	5.20	5.31	8.90	9.06	8.80	8.68	8.76	8.73		
Specific Stream Power (Wm ⁻²)	22.9	22.3	21.8	21.1	21.8	21.4	36.4	37.4	35.6	35.2	35.3	35.5		

Bankfull Hydraulic Geometry			TN	105		
Parameters	1998	1999	2000	2001	2002	2003
Area (m ²)	3.78	3.75	3.74	3.76	3.73	3.76
Width (m)	6.27	6.35	6.46	6.68	6.74	6.75
Hydraulic mean depth (m)	0.60	0.59	0.58	0.56	0.55	0.56
Maximum depth (m)	1.026	1.034	1.025	1.012	0.986	0.973
Mean velocity (ms-1)	1.14	1.13	1.11	1.09	1.08	1.09
Discharge Q (m ³ s ⁻¹)	4.33	4.23	4.16	4.12	4.04	4.09
Specific Stream Power (Wm-2)	27.8	26.8	25.9	24.9	24.2	24.4

Table 5 Bankfull hydraulic geometry parameter values for Tributary North tributary gully 1998–2003. For location of cross sections, see fig 5.

Bankfull Hydraulic Geometry			TN	106					TN	107		
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003
Area (m ²)	4.26	4.19	4.24	4.19	4.22	4.05	4.82	4.70	4.76	4.76	4.69	4.77
Width (m)	5.39	5.35	5.46	5.35	5.48	5.24	7.16	6.65	7.22	7.37	7.53	7.67
Hydraulic mean depth (m)	0.79	0.78	0.78	0.78	0.77	0.77	0.67	0.71	0.66	0.65	0.62	0.62
Maximum depth (m)	1.082	1.152	1.152	1.132	1.116	1.085	1.228	1.039	1.068	1.056	1.027	1.107
Mean velocity (ms ⁻¹)	1.37	1.36	1.36	1.36	1.35	1.35	1.23	1.27	1.21	1.20	1.17	1.17
Discharge Q (m ³ s ⁻¹)	5.85	5.72	5.74	5.71	5.68	5.47	5.94	5.98	5.78	5.70	5.50	5.58
Specific Stream Power (Wm ⁻²)	43.8	43.2	42.4	43.0	41.8	42.1	33.5	36.3	32.3	31.2	29.4	29.3

Bankfull Hydraulic Geometry			TN	108		
Parameters	1998	1999	2000	2001	2002	2003
Area (m ²)	4.30	4.24	4.22	4.26	4.25	4.33
Width (m)	6.59	7.05	7.16	7.16	7.43	7.88
Hydraulic mean depth (m)	0.65	0.60	0.59	0.59	0.57	0.55
Maximum depth (m)	1.280	1.162	1.148	1.152	1.155	1.149
Mean velocity (ms ⁻¹)	1.21	1.14	1.13	1.13	1.11	1.07
Discharge Q (m ³ s ⁻¹)	5.20	4.84	4.75	4.83	4.70	4.65
Specific Stream Power (Wm-2)	31.8	27.7	26.8	27.2	25.5	23.8

Table 5 Cont. Bankfull hydraulic geometry parameter values for Tributary North tributary gully 1998–2003.For location of cross sections, see fig 5.

5.2 Tributary Central

The location of the 15 cross sections on Tributary Central downstream of the Jabiluka mine is shown in figure 9. The Sinuous, Large Capacity and Small Capacity Reaches of Erskine et al (2001) are covered by these sections. The most upstream sites, cross sections TC06 and TC07, comprise three cross sections (labelled A, B & C) on two meander loops in the Sinuous Reach (fig 10). They were selected to determine the amount of bank erosion and lateral migration on meander loops. The remaining cross sections (except TC08) are located in the Large and Small Capacity Reaches (figs 11 & 12) which extend from the Sinuous Reach to the anabranch of Ngarradj (fig 9). Four cross sections (TC09, TC10, TC05 and TC11) are located in the Large Capacity Reach and the remaining four sections are sited in the Small Capacity Reach. Cross section TC02 is located across a distributary channel in the Small Capacity Reach. According to Folk's (1954, 1974) textural classification scheme, the bed sediments to a depth of 2.8 m on Tributary Central, were variable ranging from medium sand to slightly granular fine-coarse sand to pebbly medium-coarse sand (Erskine et al 2003).

The cross sections are shown in downstream order in Appendix B but are not numbered sequentially (fig 9). Bank height and channel capacity decrease rapidly downstream so that the channel is poorly defined where Tributary Central joins the anabranch of Ngarradj (fig 9; table 6). These channels are not flanked by a riparian vegetation community and the river banks are consequently not well protected by living trees, roots and root mats although grasses are seasonally abundant (fig 11).

For the determination of the values of the hydraulic geometry parameters in table 6, the slope used was 0.00226 m/m (2.26 m/km) which was measured from a longitudinal bed survey using differential GPS during the 1998 dry season. The Manning's n value used was 0.04. No velocity-area gaugings were undertaken on Tributary Central to check the accuracy of the estimated roughness coefficients. However, where velocity-area gauging data are available at the *eriss* stations, close correspondence between estimated and measured values was found (see below). No channel geometry results are presented for cross section TC02 because it was completely infilled with sediment during the measurement period (fig B.14, Appendix B).

5.2.1 Channel changes between 1998 and 2003

For the 14 cross sections for which hydraulic geometry parameters were determined, the changes recorded between 1998 and 2003 included:

- Cross-sectional area increased at 11 sections by up to 46%, decreased at two sections by up to 30% and was stable at one.
- Width increased at nine sections by up to 45%, decreased at three sections by up to 10% and was stable at two.
- Mean depth increased at nine sections by up to 18% and decreased at five sections by up to 23%.
- Maximum depth increased at 11 sections by up to 38% and decreased at three sections by up to 4%.
- Mean velocity increased at seven cross sections by up to 13%, decreased at five sections by up to 17% and was stable at two sections.
- Bankfull discharge increased at 11 sections by up to 56% and decreased at three sections by up to 41%.
- Specific stream power increased at nine sections by up to 33% and decreased at five sections by up to 36%.



Figure 9 Location of the permanently marked cross sections and the river reaches of Erskine et al (2001) on Tributary Central



Figure 10 Sinuous Reach of Tributary Central at cross sections TC06A, B and C



Figure 11 Large Capacity Reach of Tributary Central at cross section TC05



Figure 12 Small Capacity Reach of Tributary Central at cross section TC01 after a dry season fire. Note the low banks.

The channel changes on Tributary Central between 1998 and 2003 were the greatest of the five study reaches. The reason for the large magnitude of the changes was that many of the sections (8 of 15) were located on migrating meander loops or bends (TC06A, TC06B, TC06C, TC07A, TC07B, TC07C, TC09, TC10 and TC11). Lateral migration occurs by erosion of the outside bank of the bend (cutbank retreat) and by subsequent point bar deposition on the inside of the bend (point bar catchup). Nanson and Hickin (1983) concluded that cutbank erosion was often episodic and that point bar catchup lagged behind cutbank retreat. Cutbank erosion between 1998 and 2003 was highly variable, exhibiting the following four patterns:

- no cutbank erosion (cross section TC06A in fig B.1);
- slow progressive cutbank retreat (cross section TC06B in fig B.2);
- episodic cutbank erosion where rapid bank retreat was often followed by one to three years of no erosion (cross sections TC06C, TC07C, TC09, TC10 and TC11 in figs B.3, B.6, B.8, B.9 and B.11 respectively).
- rapid continuous cutbank erosion (cross sections TC07A and TC07B in figs B.4 and B.5 respectively).

According to Nanson and Hickin (1983) and Hickin and Nanson (1984), cutbank retreat enlarges the channel, creating the space for point bar deposition. When point bar catchup infills the erosional void, renewed cutbank erosion is initiated. Cutbank retreat enlarged the channel which either remained wider than before cutbank retreat (figs B.4, B.5, B.8 and B.9) or which rapidly contracted due to active point bar deposition (figs B.3, B.11). While channel width is essentially constant over long time periods on laterally migrating streams, there can be large variations over short time periods (1–30 years) because of low sediment supply and consequent slow point bar deposition (Nanson & Hickin 1983, 1986, Hickin & Nanson 1984).

The four downstream cross sections in the Small Capacity Reach (cross sections TC04, TC03, TC02 and TC01) are characterised by a channel perched on an actively aggrading alluvial ridge with well-developed natural levees on the right side of an alluvial fan. Cross-sectional area, mean depth and maximum depth have usually increased at the sections on the main channel, indicating that degradation is currently occurring.

Bankfull Hydraulic Geometry			тс	06A		
Parameters	1998	1999	2000	2001	2002	2003
Area (m ²)	4.87	4.53	5.19	5.92	4.84	5.20
Width (m)	10.33	10.64	10.35	10.57	10.71	10.47
Hydraulic mean depth (m)	0.47	0.43	0.50	0.56	0.45	0.50
Maximum depth (m)	0.919	1.072	1.078	1.107	0.926	1.083
Mean velocity (ms ⁻¹)	0.72	0.67	0.75	0.81	0.81	0.81
Discharge Q (m ³ s ⁻¹)	3.50	3.05	3.89	4.77	4.77	4.77
Specific Stream Power (Wm-2)	7.5	6.3	8.3	10.0	10.0	10.0

 Table 6
 Bankfull hydraulic geometry parameter values for Tributary Central 1998–2003. For locations of sections, see fig 9.

Bankfull Hydraulic Geometry	TC06C							TC07A							
Parameters	1998	1999	2000	2001	2002	2003		1998	1999	2000	2001	2002	200		
Area (m ²)	4.55	4.32	4.60	4.63	5.54	3.19		7.39	7.97	10.55	10.01	10.75	10.8		
Width (m)	8.70	7.76	7.84	8.49	11.62	7.98		11.83	12.43	14.77	15.37	16.66	17.1		
Hydraulic mean depth (m)	0.52	0.56	0.59	0.55	0.48	0.40		0.62	0.64	0.71	0.65	0.64	0.63		
Maximum depth (m)	0.982	0.912	0.962	1.177	1.059	1.010		1.169	1.150	1.258	1.220	1.285	1.14		
Mean velocity (ms-1)	0.77	0.80	0.83	0.79	0.73	0.64		0.87	0.88	0.95	0.89	0.89	0.87		
Discharge Q (m ³ s ⁻¹)	3.51	3.47	3.83	3.67	4.02	2.06		6.42	7.04	10.01	8.93	9.53	9.4		
Specific Stream Power (Wm ⁻²)	8.9	9.9	10.8	9.6	7.7	5.7		12.0	12.5	15.0	12.9	12.7	12.2		
Table 6 Cont. Bankfull hydraulic geometry parameter values for Tributary Central 1998–2003. All of the values for TC07B for each year have been recalculated from those presented in Saynor et al (2002a) as bankfull stage has changed. For locations of sections, see fig 9.

Bankfull Hydraulic Geometry			тс	07B					тс	07C		
Parameters	1998	1999	2000	2003	2002	2001	1998	1999	2000	2001	2002	2003
Area (m ²)	6.09	7.82	8.50	8.74	8.82	8.83	4.93	5.51	5.59	5.70	5.68	5.96
Width (m)	9.99	11.49	12.70	13.19	12.93	13.07	7.56	8.02	8.13	8.18	8.30	8.31
Hydraulic mean depth (m)	0.61	0.68	0.67	0.66	0.68	0.68	0.65	0.69	0.69	0.70	0.68	0.72
Maximum depth (m)	1.185	1.288	1.314	1.341	1.333	1.346	1.221	1.291	1.258	1.271	1.440	1.549
Mean velocity (ms ⁻¹)	0.85	0.92	0.91	0.90	0.92	0.91	0.89	0.93	0.93	0.93	0.92	0.95
Discharge Q (m ³ s ⁻¹)	5.19	7.18	7.72	7.89	8.12	8.07	4.40	5.10	5.17	5.32	5.24	5.67
Specific Stream Power (Wm ⁻²)	11.5	13.8	13.5	13.2	13.9	13.7	12.9	14.1	14.1	14.4	14.0	15.1

Bankfull Hydraulic Geometry			тс	:08			 		тс	:09		
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003
Area (m ²)	6.76	7.47	7.33	7.45	7.52	7.46	6.94	7.16	7.31	7.84	8.19	8.26
Width (m)	8.38	8.37	8.51	8.63	8.83	8.88	7.55	7.76	7.70	9.21	9.04	8.86
Hydraulic mean depth (m)	0.81	0.89	0.86	0.86	0.85	0.84	0.92	0.92	0.95	0.85	0.91	0.93
Maximum depth (m)	1.524	1.613	1.632	1.644	1.648	1.658	1.421	1.393	1.411	1.499	1.474	1.478
Mean velocity (ms-1)	1.03	1.10	1.07	1.08	1.07	1.06	1.12	1.13	1.15	1.07	1.11	1.13
Discharge Q (m ³ s ⁻¹)	6.95	8.22	7.88	8.03	8.02	7.89	7.80	8.07	8.38	8.37	9.11	9.37
Specific Stream Power (Wm ⁻²)	18.4	21.7	20.5	20.6	20.1	19.7	22.9	23.0	24.1	20.1	22.3	23.4

Bankfull Hydraulic Geometry			тс	:10						тс	05		
Parameters	1998	1999	2000	2001	2002	2003	-	1998	1999	2000	2001	2002	2003
Area (m ²)	3.87	3.87	3.96	4.28	4.31	4.19	-	4.95	4.83	4.86	4.81	4.64	4.85
Width (m)	7.79	7.66	7.93	8.55	8.52	8.90		5.48	5.36	5.52	5.61	5.56	5.75
Hydraulic mean depth (m)	0.50	0.50	0.50	0.50	0.51	0.47		0.90	0.90	0.88	0.86	0.83	0.84
Maximum depth (m)	0.753	0.753	0.789	0.833	0.823	0.838		1.141	1.130	1.156	1.209	1.155	1.188
Mean velocity (ms ⁻¹)	0.75	0.75	0.75	0.75	0.75	0.72		1.11	1.11	1.09	1.07	1.05	1.06
Discharge Q (m ³ s ⁻¹)	2.89	2.91	2.96	3.21	3.26	3.01		5.50	5.35	5.30	5.15	4.89	5.14
Specific Stream Power (Wm-2)	8.2	8.4	8.3	8.3	8.5	7.5		22.2	22.1	21.2	20.3	19.5	19.8

 Table 6 Cont.
 Bankfull hydraulic geometry parameter values for Tributary Central 1998–2003. For locations of sections, see fig 9.

Bankfull Hydraulic Geometry			тс	211					тс	:04		
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003
Area (m ²)	3.59	3.84	3.97	4.07	4.16	4.25	3.33	3.48	3.74	3.78	3.95	3.95
Width (m)	6.44	6.27	6.60	7.31	7.35	8.16	4.88	4.79	4.93	4.70	4.78	4.92
Hydraulic mean depth (m)	0.56	0.61	0.60	0.56	0.57	0.52	0.68	0.72	0.76	0.80	0.83	0.80
Maximum depth (m)	0.777	0.890	0.837	1.107	1.112	1.075	1.005	0.984	1.177	1.186	1.199	1.214
Mean velocity (ms ⁻¹)	0.80	0.86	0.85	0.80	0.81	0.77	0.92	0.96	0.99	1.03	1.05	1.03
Discharge Q (m ³ s ⁻¹)	2.89	3.30	3.36	3.28	3.38	3.27	3.06	3.33	3.69	3.88	4.12	4.05
Specific Stream Power (Wm ⁻²)	9.9	11.6	11.3	9.9	10.2	8.9	13.9	15.4	16.6	18.3	19.1	18.2

Bankfull Hydraulic Geometry			тс	:03						тс	:01		
Parameters	1998	1999	2000	2001	2002	2003	-	1998	1999	2000	2001	2002	2003
Area (m ²)	2.10	2.28	2.28	2.24	2.25	2.10	_	1.66	1.52	1.74	1.81	1.89	1.81
Width (m)	4.84	5.15	5.45	4.59	4.60	4.36		3.93	4.01	4.29	4.47	5.43	3.94
Hydraulic mean depth (m)	0.44	0.44	0.42	0.49	0.49	0.48		0.42	0.38	0.40	0.41	0.35	0.46
Maximum depth (m)	0.588	0.658	0.707	0.703	0.689	0.656		0.620	0.606	0.653	0.649	0.640	0.595
Mean velocity (ms-1)	0.68	0.69	0.66	0.74	0.74	0.73		0.67	0.62	0.65	0.65	0.59	0.71
Discharge Q (m ³ s ⁻¹)	1.44	1.58	1.51	1.65	1.66	1.54		1.11	0.94	1.13	1.18	1.11	1.28
Specific Stream Power (Wm-2)	6.6	6.8	6.1	7.9	8.0	7.8		6.3	5.2	5.8	5.8	4.5	7.2

Table 6 Cont. Bankfull hydraulic geometry parameter values for Tributary Central 1998–2003. For locations of sections, see fig 9.

Bankfull channel hydraulics also induce sand deposition in the Small Capacity Reach. Mean bankfull discharge over the study period changed downstream from 5.6 ± 0.9 (standard error of estimate) m³/s for the Sinuous Reach to 5.0 ± 1.3 m³/s for the Large Capacity Reach to 2.1 ± 0.8 m³/s for the Small Capacity Reach. Therefore, the frequency and duration of overbank flow increases downstream, particularly in the Small Capacity Reach. However, mean bankfull flow velocity and specific stream power are also much lower in the Small Capacity Reach than further upstream (0.88 ± 0.05 m/s and 13.2 ± 1.7 W/m² for the Sinuous and Large Capacity Reaches versus 0.78 ± 0.11 m/s and 10.0 ± 3.5 W/m² for the Small Capacity Reach).

Channel erosion by lateral migration, bed degradation and channel widening is active on Tributary Central. Clearly, Tributary Central has been unstable during the life of the Jabiluka mine. However, significant overbank deposition has also occurred on the alluvial fan in the Small Capacity Reach where distributaries, crevasses and splays are common (fig 13). Distributaries are continually developing and avulsions seem likely. While sand has been supplied to the anabranch, it terminates further downstream in a well-defined sand front and is not being transported through the anabranch to Ngarradj. Therefore, none of the sand generated by channel erosion of Tributary Central has been supplied to the Ngarradj main channel as yet.

5.2.2 Channel changes before 1998

All available vertical air photographs were stereoscopically interpreted to determine channel changes before the construction of the Jabiluka mine. The main results were:

- In 1950 the channel was well vegetated with no sand deposits and was only present upstream of the low angle distal fan which extends from cross section TC05 to the anabranch of Ngarradj.
- By 1964, extensive channel erosion had been initiated, resulting in substantial sand deposition downstream of cross section TC08. Large sand splays had been deposited on both sides of the fan immediately downstream of cross section TC05 (fig 13A).
- By 1975, the channel upstream of the fan had incised into the above sand deposits and had supplied small quantities of sand to the anabranch. The right bank channel had captured all in-channel flow at the head of the fan. Vegetation had also colonised the sand splays on the fan.
- By 1978, a continuous sand-bed channel was present from the mine to the anabranch and the Large and Small Capacity Reaches had first developed at this time. The meander loop at site TC07 had also developed and the vegetation on the inside bank of the loop had increased in density (fig 13B).
- By 1991, the loop at site TC07 had migrated rapidly downstream and the channel had evolved to its current location (fig 13C).
- By 2001, the woodland vegetation had greatly increased in density obscuring most of the channel (fig 13D).

Clearly channel erosion was initiated between 1950 and 1964, and rapidly developed up to 1975. Therefore, the initiation of channel erosion occurred before the construction of the Jabiluka mine and current channel erosion rates are lower than in the 1960s and 1970s. Furthermore, all the sand generated by channel erosion is stored in the channel, alluvial fan and anabranch without reaching Ngarradj. This lack of connectivity means that Tributary Central is currently functioning as a distinct sand compartment not integrated with the main channel.



Figure 13 Vertical air photographs of Tributary Central (A) 1964. (B) 1978



Figure 13 (continued) Vertical air photographs of Tributary Central (C) 1991. (D) 2001

5.3 East Tributary gauge

The gauging station is located in the Forested Meandering Reach of Erskine et al (2001) which is characterised by a sinuous planform (sinuosity > 1.5), steep, well-vegetated banks (monsoonal vine forest) and a sand bed (fig 14). The bed sediments to a depth of 2.8 m are dominated by granular medium sand, slightly pebbly medium-coarse sand and pebbly medium-coarse sand (Erskine et al 2003), according to Folk's (1954, 1974) textural classification scheme. Eight cross sections were installed near the gauge during the 1998 dry season. The location of the cross sections is shown in figure 15 and the cross section plots are shown in order from upstream to downstream in Appendix C. The values of the bankfull hydraulic geometry parameters for each survey at each cross section are listed in table 7.



Figure 14 East Tributary upstream of the gauging wire showing riparian vegetation and sand bed

A field surveyed flood slope (2000/2001 wet season) of 0.0015 m/m (1.5 m/km) was used to determine the value of the hydraulic geometry parameters in table 7. The Manning's n value used was 0.04. The reliability of the estimated Manning's n value was checked against the value derived from the highest (gauge height = 1.46 m) velocity-area gauging which was undertaken on 3 March 2000. The calculated Manning's n value of 0.041 agrees closely with the estimated value.

For the eight cross sections, the changes recorded between 1998 and 2003 included:

- Cross-sectional area increased at seven sections by up to 12% and decreased at one by 2%.
- Width increased at seven cross sections by up to 6% and decreased at one by 2%.
- Mean depth increased at five cross sections by up to 9%, decreased at two cross sections by up to 4% and was stable at one.

- Maximum depth increased at six cross sections by up to 25%, decreased at one cross section by 17% and was stable at one.
- Mean velocity increased at five sections by up to 6.3% and decreased at three sections by up to 3.5%.
- Bankfull discharge increased at seven sections by up to 19% and decreased at one section by 5.3%.
- Specific stream power increased at five sections by up to 17%, decreased at two sections by up to 7.3% and remained stable at one section.

Increases in area and maximum depth only exceeded 10% at one cross section (ET06), which is located at the staff gauge. Site disturbance for the operation of the gauging station may have caused these changes. The percentage decrease in maximum depth only exceeded 10% at one cross section (ET02), which is located across a step pool immediately downstream of a high log step (Marston 1982; Erskine & Webb 2003; Webb & Erskine 2003). This step pool only infilled significantly during the 2001/2002 and 2002/2003 wet seasons which were the two driest during the measurement period (Moliere et al 2002; 2003). Renewed pool scour should occur with higher streamflows.

The channel banks are stable but the bed exhibits greater changes between wet seasons (Appendix C). East Tributary is not impacted by the Jabiluka mine and is flanked by a monsoonal vine forest at the gauging station (Erskine et al 2001). Living trees, large woody debris and log and root mat steps are common in the channel (figs 16 & 17) and are important roughness elements that reduce flow velocities near the bank and stabilise the bed profile upstream of the step (Erskine 2001, Erskine & Webb 2003, Webb & Erskine 2003). Furthermore, the banks are protected by the trunks of monsoonal vine forest trees (mainly *Allosyncarpia ternata, Lophopetalum arnhemicum* and *Syzygium forte* ssp. *potamophilum*), tree roots and root mats. Sand and gravel movement through the study reach varies between wet seasons and produces spatially variable sediment storage between cross sections.

A total of 69 velocity-area gaugings were undertaken during the study period to establish and check for temporal shifts in the rating curve at the East Tributary gauge. All gaugings were conducted at the gauging wire which is located at cross section ET05 (fig 15). As shown in Figure 18A, all gaugings for all five years of the study period plot tightly around the fitted rating curve. This demonstrates that the minor channel changes outlined above have not resulted in a change in rating between 1998 and 2003. Furthermore, there have only been two gaugings at about bankfull stage and so variations in bankfull discharge over time cannot be assessed at this time. Nevertheless, the hydraulic geometry equations (Leopold & Maddock 1953) derived from the velocity-area gaugings for area and mean velocity (fig 18B & C) were used to check the reliability of the estimates from the cross-sectional surveys. The mean area and velocity at cross section ET05 between 1998 and 2003 were 5.01 m² and 0.86 m/s and agree closely with the values of 4.80 m² and 0.90 m/s respectively derived from the hydraulic geometry equations.



Figure 15 Location of the cross sections on East Tributary at the *eriss* gauging station



Figure 16 A log step and step pool in the bed of East Tributary downstream of the gauge. Log steps are important for energy dissipation in sand-bed streams.



Figure 17 Root mat step just upstream from cross section ET02 which stabilises the sandy bed material and reduces sand fluxes

nkfull Hydraulic Geometry			ET	01		
Parameters	1998	1999	2000	2001	2002	2003
Area (m ²)	8.30	8.33	9.14	8.83	8.90	8.75
Width (m)	8.07	8.13	8.17	8.29	8.46	8.56
Hydraulic mean depth (m)	1.03	1.02	1.12	1.07	1.05	1.02
Maximum depth (m)	1.510	1.459	1.759	1.671	1.749	1.552
Mean velocity (ms ⁻¹)	0.99	0.98	1.04	1.01	1.00	0.98
Discharge Q (m ³ s ⁻¹)	8.19	8.20	9.54	8.92	8.92	8.59
Specific Stream Power (Wm-2)	14.9	14.8	17.2	15.8	15.5	14.8

 Table 7
 Bankfull hydraulic geometry parameter values for the East Tributary gauge 1998–2003. For location of sections, see fig 15.

Bankfull Hydraulic Geometry			ET	⁻ 03					ET	04		
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003
Area (m ²)	7.57	7.80	8.31	7.93	8.25	8.13	6.26	6.39	6.38	6.55	6.53	6.54
Width (m)	7.65	7.63	7.68	7.74	7.85	7.96	6.85	6.85	7.04	7.11	6.69	7.01
Hydraulic mean depth (m)	0.99	1.02	1.08	1.02	1.05	1.02	0.91	0.93	0.91	0.92	0.98	0.93
Maximum depth (m)	1.518	1.603	1.654	1.614	1.626	1.587	1.261	1.321	1.320	1.336	1.397	1.339
Mean velocity (ms-1)	0.96	0.98	1.02	0.98	1.00	0.98	0.91	0.92	0.91	0.92	0.95	0.92
Discharge Q (m ³ s ⁻¹)	7.28	7.66	8.48	7.80	8.26	7.98	5.70	5.90	5.78	6.00	6.21	6.04
Specific Stream Power (Wm ⁻²)	14.0	14.8	16.2	14.8	15.5	14.7	12.2	12.7	12.1	12.4	13.6	12.7

Bankfull Hydraulic Geometry			El	05					ET	06		
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	200
Area (m ²)	4.78	4.78	4.93	5.16	5.32	5.09	5.37	5.59	5.80	5.80	5.65	6.01
Width (m)	5.95	5.99	5.98	6.02	5.90	6.05	7.25	7.33	7.38	7.41	7.37	7.38
Hydraulic mean depth (m)	0.80	0.80	0.83	0.86	0.90	0.84	0.74	0.76	0.79	0.78	0.77	0.81
Maximum depth (m)	1.166	1.187	1.247	1.274	1.255	1.179	1.137	1.197	1.318	1.324	1.343	1.41
Mean velocity (ms-1)	0.84	0.83	0.85	0.87	0.90	0.86	0.79	0.81	0.82	0.82	0.81	0.84
Discharge Q (m ³ s ⁻¹)	4.00	3.98	4.20	4.50	4.81	4.39	4.26	4.51	4.78	4.77	4.58	5.07
Specific Stream Power (Wm-2)	9.9	9.8	10.3	11.0	12.0	10.7	8.6	9.0	9.5	9.5	9.1	10.1

 Table 7 Cont.
 Bankfull hydraulic geometry parameter values for the East Tributary gauge 1998–2003. For location of sections, see fig 15.

Bankfull Hydraulic Geometry			ET	07						ET	-08		
Parameters	1998	1999	2000	2001	2002	2003	-	1998	1999	2000	2001	2002	20
Area (m ²)	8.40	8.64	8.85	9.12	8.94	8.62	-	12.14	12.60	13.30	13.04	12.96	12
Width (m)	8.81	9.39	9.30	9.44	9.52	9.13		13.64	13.45	13.58	13.48	13.84	13
Hydraulic mean depth (m)	0.95	0.92	0.95	0.97	0.94	0.94		0.89	0.94	0.98	0.97	0.94	0.
Maximum depth (m)	1.377	1.418	1.547	1.548	1.388	1.388		1.553	1.840	1.761	1.897	1.690	1.
Mean velocity (ms-1)	0.94	0.92	0.94	0.95	0.93	0.93		0.90	0.93	0.96	0.95	0.93	0.
Discharge Q (m ³ s ⁻¹)	7.87	7.91	8.30	8.63	8.30	8.03		10.88	11.68	12.70	12.35	12.00	11
Specific Stream Power (Wm-2)	13.1	12.4	13.1	13.4	12.8	12.9		11.7	12.8	13.8	13.5	12.7	1:



Figure 18 (A) Rating curve fitted to all velocity-area gaugings undertaken between 1998 and 2003 at the East Tributary gauge. (B) Hydraulic geometry data for area-discharge relationship between 1998 and 2003. (C) Hydraulic geometry data for mean velocity-discharge relationship between 1998 and 2003.

5.4 Upper Swift Creek gauge

This gauging station is located on upper Ngarradj in the Forested Meandering Reach of Erskine et al (2001) which is again characterised by a sinuous planform (sinuosity > 1.5), steep, well-vegetated banks (monsoonal vine forest) and a sand bed (fig 19). The bed sediments to a depth of 1.4 m are dominated by slightly granular medium-coarse sand and slightly pebbly fine-coarse sand (Erskine et al 2003), according to Folk's (1954, 1974) textural classification scheme. Bedrock (iron-indurated sandstone) is present close to the river bed along the right bank (Erskine et al 2003). Seven cross sections were installed near the gauge during the 1998 dry season. An additional cross section was added in 1999 (the gauging wire) and all sections have been resurveyed during each dry season up to 2003. The location of the cross sections is shown in figure 20 and the cross section plots in order from upstream to downstream are shown in Appendix D. The values of the bankfull hydraulic geometry parameters for each survey at each cross section are listed in table 8.



Figure 19 The upper Swift Creek gauging station showing the riparian vegetation and the deposition of coarse particulate organic matter during the dry season

A field-surveyed flood slope (2000/2001 wet season) of 0.00078 m/m (0.78 m/km) was used to determine the values of the hydraulic geometry parameters in table 8. The Manning's n value used was 0.035. The reliability of the estimated Manning's n value was checked against the value derived from the highest (gauge height = 1.65 m) velocity-area gauging which was undertaken on 3 March 2000. The calculated Manning's n value of 0.048 is greater than the estimated value. The reason for this discrepancy is likely to be a steeper slope than the actual value for the study reach because the reach length for the flood slope determination was very short and was located immediately downstream of bedrock bar which locally increased slope.

For the eight cross sections, the changes recorded between 1998 (1999 for cross section UMGW) and 2003 included:

- Cross-sectional area decreased at all eight sections by up to 10%.
- Width increased at five cross sections by up to 5%, decreased at one by 3% and was stable at two.
- Mean depth decreased at all eight sections by up to 11%.
- Maximum depth decreased at all eight sections by up to 14%.
- Mean velocity decreased at all eight sections by up to 8.5%.
- Bankfull discharge also decreased at all eight sections by up to 15%.
- Specific stream power decreased at five sections by up to 20% and remained stable at three sections.

The above channel changes indicate that bed aggradation has occurred at all eight cross sections. Mean depth has decreased by up to 0.13 m and maximum depth by up to 0.27 m. Therefore, sand storage in the bed has occurred during the measurement period. These channel changes induced the hydraulic adjustment of reduced bankfull mean velocity, discharge and specific stream power. This site is particularly sensitive to aggradation because of the very low bankfull specific stream power which averaged only $1.2 \pm 0.1 \text{ W/m}^2$ during the six years study period. This is very low for a stream transporting a sand load.

Upper Swift Creek gauge is not impacted by the Jabiluka mine and is flanked by a monsoonal vine forest at the gauging station (Erskine et al 2001). Recent aggradation is related to sand supply from the upstream catchment, probably from a combination of in-channel and extrachannel sources. Living trees and large woody debris are common (fig 21) and are important roughness element that reduce flow velocities near the bank and stabilise the bed profile (Erskine 2001, Erskine & Webb 2003, Webb & Erskine 2003). Furthermore, the banks are protected by the trunks of monsoonal vine forest trees (again mainly *Allosyncarpia ternata, Lophopetalum arnhemicum* and *Syzygium forte* ssp. *potamophilum*), tree roots and root mats. The combination of riparian trees and large woody debris in the channel create many sites suitable for sediment storage.

A total of 71 velocity-area gaugings were undertaken during the study period to establish and check for temporal shifts in the rating curve at the upper Swift Creek gauge. All gaugings were conducted at the gauging wire which is located at cross section UMGW (fig 20). As shown in Figure 22A, all gaugings for all five years of the study period plot tightly around the fitted rating curve. This demonstrates that the aggradation outlined above has not resulted in a change in rating between 1998 and 2003. Furthermore, there have only been three gaugings at about bankfull stage and so variations in bankfull discharge over time cannot be assessed at this time. Nevertheless, the hydraulic geometry equations (Leopold & Maddock 1953) derived from the velocity-area gaugings for area and mean velocity (fig 18B & C) were used to check the reliability of the estimates from the cross-sectional surveys. The mean area and velocity at cross section UMGW between 1999 and 2003 were 9.47 m² and 0.46 m/s and are in reasonable agreement with the values of 7.86 m² and 0.55 m/s respectively derived from the hydraulic geometry equations.



Figure 20 Location of the cross sections at the upper Swift Creek gauge



Figure 21 Large woody debris and trees in the upper Swift Creek gauge reach



Figure 22 (A) Rating curve fitted to all velocity-area gaugings undertaken between 1998 and 2003 at the upper Swift Creek gauge. (B) Hydraulic geometry data for area-discharge relationship between 1998 and 2003. (C) Hydraulic geometry data for mean velocity-discharge relationship between 1998 and 2003.

Table 8Bankfull hydraulic geometry parameter values for upper Swift Creek gauge for 1998–2003. All of the values forUM01 for each year have been recalculated as the bankfull stage has changed from what was used in Saynor et al (2002a).For location of sections, see fig 20.

Bankfull Hydraulic Geometry			UN	/101						UN	102		
Parameters	1998	1999	2000	2001	2002	2003	-	1998	1999	2000	2001	2002	2
Area (m ²)	11.88	11.64	11.68	11.71	11.85	11.57		11.25	10.77	10.67	10.88	10.70	1
Width (m)	11.08	11.29	11.05	10.69	10.67	11.21		10.21	10.13	10.21	10.36	10.33	
Hydraulic mean depth (m)	1.07	1.03	1.06	1.10	1.11	1.03		1.10	1.06	1.04	1.05	1.04	
Maximum depth (m)	1.781	1.687	1.724	1.732	1.723	1.724		1.643	1.564	1.607	1.633	1.598	
Mean velocity (ms-1)	0.46	0.45	0.45	0.46	0.47	0.45		0.47	0.45	0.45	0.45	0.45	
Discharge Q (m ³ s ⁻¹)	5.43	5.18	5.29	5.43	5.54	5.15		5.24	4.89	4.79	4.91	4.78	
Specific Stream Power (Wm-2)	1.1	1.0	1.1	1.2	1.2	1.1		1.2	1.1	1.1	1.1	1.1	

Bankfull Hydraulic Geometry			UN	103					UM	GW		
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003
Area (m²)	7.11	6.80	6.55	6.53	6.44	6.38	NA	9.46	9.51	9.63	9.42	9.31
Width (m)	7.25	7.20	7.06	6.73	6.72	7.02	NA	8.75	8.77	8.97	8.96	9.02
Hydraulic mean depth (m)	0.98	0.94	0.93	0.97	0.96	0.91	NA	1.08	1.09	1.07	1.05	1.03
Maximum depth (m)	1.277	1.202	1.241	1.303	1.188	1.131	NA	1.381	1.380	1.474	1.393	1.363
Mean velocity (ms-1)	0.43	0.42	0.41	0.43	0.42	0.41	NA	0.46	0.46	0.46	0.45	0.45
Discharge Q (m ³ s ⁻¹)	3.06	2.86	2.72	2.79	2.73	2.61	NA	4.35	4.38	4.40	4.25	4.15
Specific Stream Power (Wm-2)	1.0	0.9	0.9	0.9	0.9	0.8	NA	1.1	1.1	1.1	1.1	1.1

Bankfull Hydraulic Geometry			UN	/104					UN	105		
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	
Area (m ²)	10.66	10.35	10.66	10.69	10.84	10.55	11.53	11.25	11.27	11.23	11.28	
Width (m)	9.36	9.35	9.41	9.36	9.48	9.55	9.97	9.94	10.09	10.03	10.03	
Hydraulic mean depth (m)	1.14	1.11	1.13	1.14	1.14	1.11	1.16	1.13	1.12	1.12	1.12	
Maximum depth (m)	1.574	1.471	1.471	1.574	1.556	1.469	1.551	1.483	1.479	1.490	1.466	
Mean velocity (ms-1)	0.48	0.47	0.47	0.48	0.48	0.47	0.48	0.47	0.47	0.47	0.47	
Discharge Q (m ³ s ⁻¹)	5.07	4.83	5.05	5.09	5.17	4.92	5.54	5.33	5.29	5.28	5.32	
Specific Stream Power (Wm-2)	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.2	1.2	1.2	1.2	

Table 8 Cont. Bankfull hydraulic geometry parameter values for upper Swift Creek gauge for 1998–2003. For location of sections, see fig 20.

Bankfull Hydraulic Geometry			UN	106			UM07					
Parameters	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003
Area (m ²)	14.24	14.09	14.06	14.01	13.95	13.84	15.96	15.36	15.49	14.97	15.26	14.77
Width (m)	12.26	12.14	12.83	12.32	12.27	12.18	11.60	11.60	11.54	11.54	11.60	11.65
Hydraulic mean depth (m)	1.16	1.16	1.10	1.14	1.14	1.14	1.38	1.32	1.34	1.30	1.32	1.27
Maximum depth (m)	1.545	1.535	1.504	1.504	1.499	1.490	1.927	1.797	1.923	1.74	1.831	1.656
Mean velocity (ms ⁻¹)	0.48	0.48	0.46	0.48	0.48	0.47	0.54	0.53	0.53	0.52	0.52	0.51
Discharge Q (m ³ s ⁻¹)	6.86	6.79	6.52	6.66	6.63	6.57	8.61	8.08	8.22	7.77	7.99	7.54
Specific Stream Power (Wm ⁻²)	1.3	1.3	1.2	1.2	1.2	1.2	1.7	1.6	1.6	1.5	1.6	1.5

5.5 Swift Creek gauge

This gauging station is located in the Sinuous Reach of Erskine et al (2001) which is characterised by a sinuous planform (sinuosity > 1.2 but < 1.5), by less steep and less well vegetated (mixed paperbark and monsoonal vine forest), sandy banks than upstream where there is a monsoonal vine forest, and by a sand bed (fig 23). The bed sediments to a depth of 1.2 m are dominated by slightly granular medium sand (Erskine et al 2003), according to Folk's (1954, 1974) textural classification scheme. Eight cross sections were installed near the gauge during the 1998 dry season. The location of the cross sections is shown in figure 24 and the cross section plots are shown in order from upstream to downstream in Appendix E.

The values of the bankfull hydraulic geometry parameters for each survey at each cross section are listed in table 9. A field-surveyed bed slope of 0.00095 m/m (0.95 m/km) was used to determine the values of the hydraulic geometry parameters in table 9. The Manning's n value used was 0.035. The reliability of the estimated Manning's n value was checked against the value derived from the highest (gauge height = 1.98 m) velocity-area gauging which was undertaken on 3 March 2000. The calculated Manning's n value of 0.0356 agrees closely with the estimated value.



Figure 23 Swift Creek gauge site

For the eight cross sections, the changes recorded between 1998 and 2003 included:

- Cross-sectional area decreased at five cross sections by up to 10% and was stable at three sections.
- Width increased at five cross sections by up to 14%, decreased at one section by 4% and was stable at two sections.
- Mean depth increased at one cross section by 1.1%, decreased at six sections by up to 17% and was stable at one section.
- Maximum depth increased at seven sections by up to 17% and decreased at one by 3%.

- Mean velocity decreased at six sections by up to 12%, increased at one section by 1.3% and remained stable at one section.
- Bankfull discharge decreased at seven sections by up to 18% and remained stable at one section.
- Specific stream power decreased at six sections by up to 26%, increased at one section by 3.1% and remained stable at one section.

This site is located downstream of the Jabiluka mine. However, sand storage in the bed, as evidenced by decreases in cross-sectional area at five sections and decreases in mean depth at six sections, was also recorded over the same time period at upper Swift Creek gauge. Furthermore, the sand generated by channel erosion on Tributary Central is completely stored in the channel and fan of Tributary Central and the upstream anabranch of Ngarradj without being supplied to the main channel (see section 5.2). Contemporary bank erosion rates on Tributary North, as measured by erosion pins over three years, are significant (Saynor et al 2003) and the cross sections of the main gully also indicate active bed and bank erosion. Therefore, Tributary North is certainly supplying sand to Ngarradj immediately upstream of the Swift Creek gauge. However, the masses involved are small (see section 7). Nevertheless, substantial bed aggradation was recorded at the upper Swift Creek gauge (see section 5.4) and hence the upper Ngarradj catchment is likely to be the most important sand source.

A total of 75 velocity-area gaugings were undertaken during the study period to establish and check for temporal shifts in the rating curve at the Swift Creek gauge. All gaugings were conducted at the gauging wire which is located at cross section SM06 (fig 24). As shown in Figure 25A, all gaugings for all five years of the study period plot tightly around the fitted rating curve. This demonstrates that the aggradation outlined above has not resulted in a change in rating between 1998 and 2003. Furthermore, there have only been two gaugings at about bankfull stage and so variations in bankfull discharge over time cannot be assessed at this time. Nevertheless, the hydraulic geometry equations (Leopold & Maddock 1953) derived from the velocity-area gaugings for area and mean velocity (fig 25B & C) were used to check the reliability of the estimates from the cross-sectional surveys. The mean area and velocity at cross section SM06 between 1998 and 2003 were 17.3 m² and 0.86 m/s and are in reasonable agreement with the values of 22.3 m² and 0.67 m/s respectively derived from the hydraulic geometry equations.



Figure 24 Location of cross sections at the Swift Creek gauge



Figure 25 (A) Rating curve fitted to all velocity-area gaugings undertaken between 1998 and 2003 at the Swift Creek gauge. (B) Hydraulic geometry data for area-discharge relationship between 1998 and 2003. (C) Hydraulic geometry data for mean velocity-discharge relationship between 1998 and 2003.

full Hydraulic Geometry			SN	105		
Parameters	1998	1999	2000	2001	2002	2003
Area (m ²)	21.53	20.40	20.27	20.24	23.09	20.39
Width (m)	19.23	18.89	19.05	19.05	20.04	21.96
Hydraulic mean depth (m)	1.12	1.08	1.06	1.06	1.15	0.93
Maximum depth (m)	1.702	1.613	1.681	1.772	2.171	1.855
Mean velocity (ms-1)	0.95	0.93	0.92	0.92	0.97	0.84
Discharge Q (m ³ s ⁻¹)	20.48	18.93	18.63	18.58	22.37	17.12
Specific Stream Power (Wm-2)	9.9	9.4	9.1	9.1	10.4	7.3

 Table 9
 Bankfull hydraulic geometry parameter values for the Swift Creek gauge for 1998–2003. For location of sections, see fig 24.

Bankfull Hydraulic Geometry		SM02						SM01					
Parameters	1998	1999	2000	2001	2002	2003		1998	1999	2000	2001	2002	
Area (m²)	18.28	17.17	16.66	16.82	17.04	17.39		10.35	9.89	9.89	10.20	10.42	
Width (m)	19.56	20.38	19.81	19.68	19.67	19.79		10.75	11.30	11.05	11.02	10.85	
Hydraulic mean depth (m)	0.93	0.84	0.84	0.85	0.87	0.88		0.96	0.88	0.89	0.93	0.96	
Maximum depth (m)	1.522	1.421	1.456	1.495	1.528	1.474		1.431	1.356	1.313	1.565	1.566	
Mean velocity (ms-1)	0.84	0.79	0.79	0.79	0.80	0.81		0.86	0.81	0.82	0.84	0.86	
Discharge Q (m ³ s ⁻¹)	15.40	13.51	13.09	13.35	13.65	14.07		8.89	7.98	8.09	8.55	8.95	
Specific Stream Power (Wm ⁻²)	7.3	6.2	6.2	6.3	6.5	6.6		7.7	6.6	6.8	7.2	7.7	

kfull Hydraulic Geometry			SN	106		
Parameters	1998	1999	2000	2001	2002	2003
Area (m²)	17.57	17.09	16.91	17.14	17.56	17.52
Width (m)	17.99	17.63	17.78	17.43	17.76	18.59
Hydraulic mean depth (m)	0.98	0.97	0.95	0.98	0.99	0.94
Aaximum depth (m)	1.763	1.697	1.691	1.745	1.876	1.785
Mean velocity (ms ⁻¹)	0.87	0.86	0.85	0.87	0.87	0.85
Discharge Q (m ³ s ⁻¹)	15.25	14.76	14.42	14.95	15.36	14.86
Specific Stream Power (Wm ⁻²)	7.9	7.8	7.6	8.0	8.1	7.5

 Table 9 Cont.
 Bankfull hydraulic geometry parameter values for the Swift Creek gauge for 1998–2003. For location of sections, see fig 24.

Bankfull Hydraulic Geometry		SM07						SM08					
Parameters	1998	1999	2000	2001	2002	2003		1998	1999	2000	2001	2002	2003
Area (m ²)	18.87	18.16	17.64	17.54	18.98	18.83		19.75	18.74	18.21	18.37	18.46	18.68
Width (m)	15.05	14.77	15.61	14.82	15.29	15.08		18.80	18.65	18.68	18.55	18.84	18.73
Hydraulic mean depth (m)	1.25	1.23	1.13	1.18	1.24	1.25		1.05	1.01	0.97	0.99	0.98	1.00
Maximum depth (m)	1.768	1.662	1.651	1.751	2.002	2.062		1.717	1.53	1.634	1.603	1.755	1.785
Mean velocity (ms ⁻¹)	1.03	1.01	0.96	0.99	1.02	1.02		0.91	0.88	0.87	0.88	0.87	0.88
Discharge Q (m ³ s ⁻¹)	19.35	18.38	16.88	17.30	19.33	19.26		18.00	16.58	15.79	16.09	16.06	16.44
Specific Stream Power (Wm-2)	12.0	11.6	10.1	10.9	11.8	11.9		8.9	8.3	7.9	8.1	8.0	8.2

6 Hydraulic influences on recent channel changes

The influence of the hydraulic parameters (bankfull mean velocity, bankfull discharge and bankfull specific stream power) in tables 4 to 9 inclusive on recent channel changes was investigated by determining product moment correlation coefficients between mean values of these parameters (1998–2003) and the percentage change in channel geometry over the same time period at each cross section for each study reach. Percentage change in bankfull area, width, mean depth and maximum depth at each cross section was calculated by:

$$((V_2/V_1) - 1) \times 100$$
 (7)

where V_1 is the value of the hydraulic geometric parameter in 1998 and V_2 is the corresponding value in 2003.

At the gauging wire cross section at the upper Swift Creek gauge, the relevant values for 1999 were used for V_1 (table 8). The results are presented in table 10 and are discussed below for each site.

6.1 Tributary North

6.1.1 Tributary North main gully

There were no significant correlations at this site (table 10). However, there is an inverse relationship between percentage change in all hydraulic geometry parameters and mean bankfull hydraulic parameters. Such inverse relationships are expected for gullies, as discussed below.

6.1.2 Tributary North tributary gully

Percentage change in area, width and maximum depth between 1998 and 2003 are significantly correlated with mean bankfull flow velocity and mean bankfull specific stream power (table 10). The first two are negatively or inversely related whereas the last one is positively related. The inverse relationship is unusual but can be explained by active incision that is occurring near the nickpoint. Erskine (1999, 2005) discussed the processes of channel incision and gully erosion and concluded that initial rapid incision by upstream nickpoint retreat is followed by substantial gully widening and downstream progressing degradation before gully stabilisation occurs. There is a rapid, logarithmic or exponential decline in sediment yields by gully erosion for the first 20 years after gully initiation (Erskine 2005) and so active enlargement ceases about 20 years after initial incision. This gully had been initiated by 1987 and should now be approaching the end of this rapid erosion phase. The reason for the inverse relationship between percentage change in area and width, and the hydraulic parameters is that the unstable sites are those with the smallest cross-sectional area that are undergoing active enlargement and widening near the primary nickpoint whereas the enlarged cross sections further downstream are less dynamic and exhibit minor contemporary change. The positive correlation between percentage change in maximum depth and mean bankfull flow velocity and specific stream power indicates that thalweg scour is greatest at sites of greatest hydraulic stress.

Figure 26 shows the regressions of percentage change in area, width and maximum depth between 1998 and 2003, and mean bankfull specific stream power for the same time period. The simple linear correlations and regressions are significant. The relationship between maximum depth and specific stream power is curvilinear with the quadratic equation resulting in a significant increase in the explained variance over the linear equation. Furthermore, the turning point at about 29 W/m² may also represent a stability threshold for the process of channel incision (Erskine 1999).

Table 10 Correlation coefficients of mean bankfull hydraulic parameter values between 1998 and 2003 and percentage change in hydraulic geometry parameters between 1998 and 2003. Values significant at the 5% level are marked by an asterisk and values significant at the 1% level are marked by two asterisks.

Site	Hydraulic Geometry Parameter	Mean Bankfull Flow Velocity	Mean Bankfull Discharge	Mean Bankfull Specific Stream Power
	Area	-0.404	-0.567	-0.381
Tributary North	Width	-0.134	-0.415	-0.141
n = 8	Mean Depth	-0.494	-0.360	-0.440
	Maximum Depth	-0.628	-0.569	-0.584
	Area	-0.932**	-0.395	-0.932**
Tributary North	Width	-0.806*	-0.340	-0.807*
n = 5	Mean Depth	0.702	0.261	0.704
	Maximum Depth	0.717*	0.052	0.734*
	Area	0.280	0.562*	0.236
Tributary Central	Width	0.083	0.550	0.081
n = 14	Mean Depth	0.294	0.152	0.261
	Maximum Depth	0.132	-0.096	0.063
	Area	-0.825*	-0.781*	-0.821*
East Tributary gauge	Width	0.204	-0.215	0.173
n = 8	Mean Depth	-0.821*	-0.565	-0.800*
	Maximum Depth	-0.840**	-0.755*	-0.831*
	Area	0.162	0.162	0.104
Upper Swift Creek	Width	0.114	0.099	0.080
n = 8	Mean Depth	0.070	0.095	0.032
	Maximum Depth	-0.327	-0.199	-0.378
	Area	0.263	-0.293	0.272
Swift Creek gauge	Width	0.292	0.538	0.263
n = 8	Mean Depth	-0.035	-0.514	-0.008
	Maximum Depth	0.728*	0.576	0.735*



Figure 26 Regressions of average bankfull specific stream power on percentage change in area, width and maximum depth between 1998 and 2003 on Tributary North tributary gully

6.2 Tributary Central

The only significant correlation was between percentage change in area between 1998 and 2003 and mean bankfull discharge for the same time period. Channel planform exerted a strong control on changes in hydraulic geometry on Tributary Central because the greatest changes were associated with lateral migration of meander loops (section 5.2). Therefore, a close association between channel changes and channel hydraulics would not be expected for a channel exhibiting a range of channel planforms.

6.3 East Tributary gauge

There were many significant correlations at this site (table 10). Changes in area, mean depth and maximum depth between 1998 and 2003 were inversely correlated with average mean flow velocity, bankfull discharge and/or bankfull specific stream power for the same time period. Figure 27 shows the regressions for changes in channel geometry against mean flow velocity. These regressions cover a very small range on both the abscissa (x axis) and ordinate (y axis), and hence are unduly influenced by two extreme values, one with a low and one with a high mean flow velocity. While these correlations are statistically significant they are not geomorphologically meaningful.

6.4 Upper Swift Creek gauge

There were no significant correlations at this site. This lends further support to the cause of recent aggradation being due to increased sediment supply from the upstream catchment, probably from both in- and extra-channel sediment sources.

6.5 Swift Creek gauge

There were two significant correlations at this site (table 10). Percentage change in maximum depth between 1998 and 2003 was positively related to mean bankfull flow velocity and specific stream power for the same time period. This indicates that scour of the thalweg was closely associated with sites of greatest hydraulic stress.



Figure 27 Regressions of average bankfull mean flow velocity and percentage change in area, mean depth and maximum depth between 1998 and 2003 at the East Tributary gauge. Note the two extreme flow velocity values, one low and one high, and their influence on the regression.

7 Channel erosion in Ngarradj catchment between 1998 and 2003

The contribution of sediment by large-scale channel erosion (bank erosion and bed degradation) to the study reaches in the Ngarradj catchment for each year between 1998 and 2003 as well as for the total period was calculated by multiplying the average change in cross-sectional area by the study reach length (table 11). The latter values are the same as those used by Saynor et al (2003) for the calculation of sediment supply by small-scale bank erosion measured with erosion pins over three years. The volumes were converted to mass by assuming a uniform sediment bulk density of 1.5 t/m³, also following the practice of Saynor et al (2003).

	Change in sediment Erosion/Deposition (tonnes)											
Reach	1998/1999	1999/2000	2000/2001	2001/2002	2002/2003	1998/2003						
Tributary North main gully	58	-36	3	6	13	40						
Tributary North tributary gully	-9	1	-1	-2	0	-10						
Tributary Central	266	227	81	93	-80	587						
East Tributary gauge	23	35	-2	-11	-11	32						
Upper Swift Creek gauge	-53	3	-5	2	-31	-78						
Swift Creek gauge	-180	-95	48	101	-29	-150						
Total	105	135	124	189	-138	421						
Total without Tributary Central	-161	-92	43	96	-58	-166						

Table 11 Summary of change in sediment erosion/deposition for each study reach in the Ngarradjcatchment between 1998 and 2003. Positive values indicate the mass of erosion (tonnes) and negativevalues, the mass of deposition (tonnes).

It must be emphasised that the sediment masses in table 11 only refer to the measurement reaches which vary in length from 65 m to 681 m. Nevertheless, there are a number of important trends revealed by these results:

- Tributary Central is the most active measured sediment source in terms of channel erosion in the Ngarradj catchment.
- The main gully on Tributary North also generates small amounts of sediment but the tributary gully is currently a net sediment store.
- Sediment storage in the channel network is the main geomorphic process in the three gauging station reaches where there is a distinctive riparian forest community.
- The measurement reaches in the channel network are a net sediment source, due mainly to the high rates of channel erosion on Tributary Central.
- The sediment generated by channel erosion on Tributary Central is not supplied to the main channel of Ngarradj but is stored in the channel and fan of Tributary Central and the anabranch of Ngarradj.
- The results in table 11 are so greatly influenced by the results for Tributary Central that when it is removed sediment storage dominates (table 11).
- Each measurement reach alternates between a sediment source and a sediment store over time and the trends are not synchronous between reaches.
- The manipulations of the data in table 11 are based on simple arithmetic means and channel lengths for the study reaches. Further manipulations of the data are warranted for the construction of the sediment budget.

8 Scour chain results

Data for the 1998/1999, 1999/2000 and 2000/2001 wet seasons are contained in Saynor et al (2002b) and those for the 2001/2002 and 2002/2003 wet seasons are contained in Saynor et al (2004b).

8.1 Tributary North

Chains were installed during the late dry season of 1999 at six cross sections in the Gullied Reach (fig 28). The following narrow cross sections had a single chain installed in the centre of the main gully: TN02, TN04 and TN07. Two chains were installed in the bed at the most downstream and widest cross section (TN09) on the main gully. The tributary gully had a single chain installed in the middle of the narrow bed on cross sections TN05 and TN07. The location of the cross sections with scour chains is shown in figure 28. The scour chain results are combined for both the main and tributary gullies due to the small sample size.

Table 12 shows the scour and fill at each section for each year and summarises the reach average scour and fill for each wet season between 1999/2000 and 2002/2003 inclusive.

		1999/2000			2000/2001	
Cross Section	Scour	Fill	Net Change	Scour	Fill	Net Change
TN02 main gully	219	169	-50	186	112	-74
TN04 main gully	0	60	60	110	69	-41
TN05 tributary gully	35	67	32	0	14	14
TN07 main gully	38	70	32	82	104	22
TN07 tributary gully	0	40	40	90	15	-75
TN09 main gully Average	8	45	37	20	22	2
Average	50 ± 34	75 ± 19	25 ± 16	81 ± 27	56 ± 18	-25 ± 18
		2001/2002				
Cross Section	Scour	Fill	Net Change	Scour	Fill	Net Change
TN02 main gully	68	95	27	0	180	180
TN04 main gully	90	0	-90	0	75	75
TN05 tributary gully	0	20	20	0	36	36
TN07 main gully	75	0	-75	0	76	76
TN07 tributary gully	0	60	60	130	130	0
TN09 main gully Average	27	51	24	0	13	13
Average	33 ± 23	28 ± 16	-6 ± 25	22 ± 22	85 ± 25	63 ± 27

 Table 12
 Scour and fill on Tributary North. The standard error of estimate of the mean is also shown for the averages. All units are in mm.

Average annual scour and fill for the reach, allowing for plus or minus twice the standard error of estimate of the mean, overlap with each other for every year of record. The net change in scour and fill for Tributary North was determined by subtracting the depth of scour from the depth of fill. A positive value indicates net fill and a negative value, net scour. The maximum scour was 219 mm at cross section TN02 during the 1999/2000 wet season and the maximum fill was 180 mm also at cross section TN02 during the 2002/2003 wet season. There was average net fill of 25 ± 16 mm for the 1999/2000 wet season, average net scour of

 25 ± 18 mm for the 2000/2001 wet season, average net scour of 6 ± 25 mm for the 2001/2002 wet season and average net fill of 63 ± 27 mm for the 2002/2003 wet season (table 12). These values overlap with each other for successive wet seasons, allowing for plus or minus twice the standard error of estimate of the mean. While the net change appears to be cyclic, with net fill alternating with net scour over 1–2 year time periods, a larger sample size would be required to determine if this cyclic trend is statistically significant.

8.2 Tributary Central

A single chain was located in the centre of the river bed on each of three cross sections, TC09, TC11 and TC03, before the 1998/1999 wet season (fig 9). The first two cross sections are located in the Large Capacity Reach and the last, in the Small Capacity Reach (fig 9). Table 13 shows the scour and fill at each section for each year and the site average for each wet season. Average scour and fill for each year, allowing for plus or minus twice the standard error of estimate of the mean, overlap with each other for every year of record. The maximum scour was 249 mm at cross section TC03 during the 1988/1999 wet season and maximum fill was 340 mm at cross section TC11 during 2000/2001 wet season. There was average net scour of 7 ± 23 mm for 1999/2000 wet season, average net fill of 97 ± 91 mm for 2000/2001 wet season, average net scour of 7 ± 20 mm for 2001/2002 wet season and average net fill of 12 ± 20 mm for 2002/2003 wet season. These site average values also overlap with each other for successive years, allowing for plus or minus twice the standard error of estimate of the sample size is too small to determine whether these trends are statistically significant.

Cross -	1	1998/1999			1999/2000)		2000/2001			
Section	Scour	Fill	Net Change	Scour	Fill	Net Change	Scour	Fill	Net Change		
TC09				40	40	0	13	13	0		
TC11				61	11	-50	60	340	280		
TC03	249	324	75	148	178	30	144	156	12		
Average	N/A	N/A	N/A	83 ± 33	76 ± 52	-7 ± 23	72 ± 38	170 ± 95	97 ± 91		

 Table 13
 Scour and fill on Tributary Central. The standard error of estimate is also shown for the averages. All units are in mm.

Cross		2001/2002	2	2002/2003				
Section	Scour	Fill	Net Change	Scour	Fill	Net Change		
TC09	20	20	0	15	0	-15		
TC11	60	0	-60	0	0	0		
TC03	90	130	40	70	120	50		
Average	57 ± 20	50 ± 40	-7 ± 29	28 ± 21	40 ± 40	12 ± 20		



Figure 28 Location of the scour chains in the Gullied Reach of Tributary North

8.3 East Tributary gauge

Scour chains were installed at four cross sections at the East Tributary gauging station before the 1998/99 wet season. Two chains were located on cross section ET01 and one chain was located on cross sections ET04, ET07 and ET08 (fig 15). Lack of time before the commencement of runoff at the start of the 1998/99 wet season prevented the installation of additional chains at the latter sections.

Table 14 shows the scour and fill at each section for each year and summarises the reach average scour and fill for each wet season between 1998/1999 and 2002/2003 inclusive. Average scour and fill for each year, allowing for plus or minus twice the standard error of estimate of the mean, overlap with each other for every year of record. The maximum scour was 350 mm at cross section ET01 during the 1998/1999 wet season and the maximum fill was 470 mm at the same section during the same wet season. There was average net fill of 32 ± 76 mm for the 1998/1999 wet season, average net scour of 29 ± 19 mm for the 1999/2000 wet season, average net fill of 2 ± 14 mm for 2000/2001 wet season, average net fill of 2002/2003 wet season. These reach average values also overlap with each other for successive wet seasons, allowing for plus or minus twice the standard error of estimate of the mean. Net change may be cyclic with net scour alternating with net fill over time periods of 1-3 years but the sample size is too small to differentiate natural variability from a trend.

	1998/1999				1999/2000	1	2000/2001			
Cross Section	Scour	Fill	Net Change	Scour	Fill	Net Change	Scour	Fill	Net Change	
ET01 Average	350*	470*	120	243	162	-81	163	199	36	
ET04				108	108	0	130	100	-30	
ET07	159	255	96	298	298	0	255	255	0	
ET08	270	150	-120	146	111	-35	107	107	0	
Average	260 ± 55	292 ± 94	32 ± 76	199 ± 44	170 ± 45	$\textbf{-29}\pm\textbf{19}$	164 ± 33	165 ± 37	2 ± 14	

Table 14Scour and fill at the East Tributary gauging station. The standard error of estimate is alsoshown for the averages. All units are in mm.

		2001/2002		2002/2003				
Cross Section	Scour	Fill	Net Change	Scour	Fill	Net Change		
ET01 Average	148	148	30	135	268	133		
ET04	40	135	95	140	85	-55		
ET07	192	215	23	280	290	10		
ET08	107	95	-12	55	175	120		
Average	122 ± 32	148 ± 25	27 ± 24	153 ± 47	205 ± 47	52 ± 45		

* Determined only from ET01-2

8.4 Upper Swift Creek gauge

Two scour chains were installed at three cross sections (UM02, UM05 and UM07) at the upper Swift Creek gauging station before the 1998/99 wet season. The location of the cross sections is shown in figure 20.

Table 15 shows the average scour and fill at each section for each year and summarises the reach average scour and fill for each wet season between 1998/1999 and 2002/2003 inclusive. Average scour and fill at each section, allowing for plus or minus twice the standard error of estimate of the mean, overlap with each other for every year of record. The maximum average scour was 370 mm at cross section UM02 during the 2000/2001 wet season and the maximum average fill was 410 mm at the same section during the same wet season. There was net fill recorded for the reach for every year of measurements. This confirms the aggradation recorded by the cross section results (section 5.4). While the reach average values overlap with each other, allowing for plus or minus twice the standard error of estimate of the mean for successive wet years between 1999/2000and 2002/2003, this is not the case between the 1988/1999 and 1999/2000 wet seasons. The first wet season recorded the greatest net fill for the whole measurement period

Table 15Scour and fill at the upper Swift Creek gauge. The standard error of estimate is also shown for
the averages. All units are in mm.

	1998/1999			1999/2000			2000/2001		
Cross Section	Scour	Fill	Net Change	Scour	Fill	Net Change	Scour	Fill	Net Change
UM02 Average	138	360	222	257	266	9	267	279	12
UM05 Average	94	183	89	116	135	19	99	120	21
UM07 Average	187	302	115	162	196	34	213	222	9
Average	140 ± 27	282 ± 52	142 ± 41	178 ± 42	199 ± 38	21 ± 7	193 ± 50	207 ± 46	14 ± 4

		2001/2002	!	2002/2003			
Cross Section	Scour	Fill	Net Change	Scour	Fill	Net Change	
UM02 Average	333	355	23	370	410	40	
UM05 Average	210	210	0	143	150	8	
UM07 Average	253	255	3	248	283	35	
Average	265 ± 36	$\textbf{273} \pm \textbf{43}$	9 ± 7	254 ± 66	281 ± 75	28 ± 10	

* Scour chain UM02-2 exhibited no vertical links when excavated after the 1998/99 wet season, therefore, scour was only determined from UM02-1. The fill was the average fill for both chains.

8.5 Swift Creek gauge

Three scour chains were installed at cross sections SM05 and SM08 at the Swift Creek gauging station before the 1998/99 wet season. Three chains were installed at cross section SM02 before the 1999/2000 wet season. The location of the cross sections is shown in figure 24.

Table 16 shows the scour and fill at each section for each wet season and summarises the average scour and fill for the reach for each wet season between 1998/1999 and 2002/2003 inclusive. Average scour and fill at each section for each year of record, allowing for plus or minus twice the standard error of estimate of the mean, overlap with each other. The maximum average scour was 505 mm at cross section SM05 during the 2000/2001 wet season
and the maximum average fill was 530 mm at the same section for the same wet season. There was average net fill of 80 ± 8 mm for the 1998/1999 wet season, average net fill of 23 ± 18 mm for the 1999/2000 wet season, no net change for the 2000/2001 wet season, insufficient data to calculate a mean for the 2001/2002 wet season and net scour of 33 ± 24 mm for the 2002/2003 wet season. While site average values overlap with each other, allowing for plus or minus twice the standard error of estimate of the mean for successive wet seasons between 1999/2000 and 2002/2003, this is not the case between the 1998/1999 and 1999/2000 wet seasons. The first wet season recorded the greatest net fill for the measurement period but is based on the smallest sample size.

	1998/1999			1999/2000			2000/2001		
Cross Section	Scour	Fill	Net Change	Scour	Fill	Net Change	Scour	Fill	Net Change
SM05 Average	362	434	72	376	405	29	505	530	25
SM02 Average	Not installed			184	173	-11	187	189	2
SM08 Average	260	348	88	257	307	50	303	275	-25
Average	311 ± 51	391 ± 43	80 ± 8	272 ± 56	295 ± 67	23 ± 18	332 ± 93	331 ±102	0 ± 15

 Table 16
 Scour and fill at the Swift Creek gauge. The standard error of estimate is also shown for the averages. All units are in mm.

		2001/2002		2002/2003		
Cross Section	Scour	Fill	Net Change	Scour	Fill	Net Change
SM05 Average	Not Found			Not Found		
SM02 Average	Pig Damage, Not measured			125	68	-57
SM08 Average	159	199	40	337	329	-8
Average	N/A	N/A	N/A	231 ± 106	199 ± 130	$\textbf{-33}\pm\textbf{24}$

* Scour chain SM05-3 was not located in 2000/2001 and SM05-2 was completely dislodged during the 1998/99 wet season. Therefore, scour was only determined from chain SM05-1 and fill was determined from two chains (SM05-1 & 2).

9 Scour and fill in Ngarradj catchment

Table 17 shows the average values of net change in scour and fill for each study reach in the Ngarradj catchment for each year of measurement. Again scour is denoted by a negative value and fill by a positive value.

Except for the 1998/1999 wet season when there were less data, both net scour and net fill were recorded in the study reaches for each wet season. The mine site tributaries alternated between net scour and net fill over 1–2 year time periods. Net fill dominated in the three gauging station reaches. The results of one year measurements of scour and fill, as carried out by Roberts (1991) on Magela Creek, are likely to yield little information on longer term trends and, therefore, one year of measurements is not recommended for future use in the Alligator Rivers Region. Furthermore, given the variance in the scour and fill data, at least 10 chains should be installed in a measurement reach to reliably estimate mean values.

Reach	1998/1999	1999/2000	2000/2001	2001/2002	2002/2003
	Scour/Fill	Scour/Fill	Scour/Fill	Scour/Fill	Scour/Fill
Tributary North	Not Installed	25 ± 16	$\textbf{-25}\pm\textbf{18}$	-6 ± 25	63 ± 27
Tributary Central	Insufficient Data	-7 ± 23	97 ± 91	-7 ± 29	12 ± 20
East Tributary gauge	32 ± 76	-29 ± 19	2 ± 14	27 ± 24	52 ± 45
Upper Swift Creek gauge	142 ± 41	21 ± 7	14 ± 4	9 ± 7	28 ± 10
Swift Creek gauge	80 ± 8	23 ± 18	0 ± 15	Insufficient Data	$\textbf{-33}\pm\textbf{24}$
Average	85 ± 28	7 ± 11	18 ± 21	6 ± 8	24 ± 17

Table 17 Mean values of net change in scour (negative values) and fill (positive values) and thestandard error of estimate for each reach in which scour chain measurements were made for each wetseason. All units are in mm.

The catchment average net scour and fill was calculated as the arithmetic mean of the averages for each measurement reach (table 17). Alternative weightings could be used, such as one based on reach length. On a catchment scale, fill occurred for all five years. However, the standard error of estimate was large in relation to the mean for all years of measurement, except the first, which had less data than subsequent years. However, the current data are not sufficiently reliable to preclude net scour. Furthermore, net scour was recorded in at least one measurement reach for all years, except the first.

The scour chain measurements indicate that minor net fill is currently occurring in the Ngarradj catchment and hence the bed is an active sand storage. Therefore, it is essential that effective sediment control measures are maintained on the Jabiluka mine site because minederived sand will be quickly routed to the channel network where it will be temporarily stored. The scour chain measurements do not indicate that the mine site tributaries (Tributary North and Tributary Central) have been oversupplied with sand derived from the mine site because active bed aggradation is not currently occurring.

Roberts (1991) interpreted scour depths, as measured by scour chains, as being related to onehalf of the maximum dune (large scale ripple) amplitude. If this interpretation is correct, the range of maximum dune amplitudes for the study reaches for the measured wet seasons are:

- 44 ± 44 to 162 ± 54 mm on Tributary North,
- 56 ± 42 to 166 ± 66 mm on Tributary Central,
- 244 ± 62 to 520 ± 110 mm at the East Tributary gauge,
- 280 ± 54 to 530 ± 72 mm at upper Swift Creek gauge, and
- 462 ± 212 to 664 ± 186 mm at the Swift Creek gauge.

Field observations of bedform dimensions during each wet season indicate that these estimated values are in reasonable agreement with measured/estimated maximum values during weekly site visits to the gauging stations. They also indicate that dune dimensions are least on the mine site tributaries (the smallest channels) and greatest at the gauging stations (the largest channels), with the largest bedforms at the Swift Creek gauge which has the greatest catchment area and discharge.

The data in table 17 have been converted to sediment masses in table 18 by again using the same measurement reach lengths as used for table 11 and a uniform sediment bulk density of

 1.5 t/m^3 . The signs are the opposite of those used for the cross-sectional data in table 11 to be consistent with the text and the scour and fill literature.

The scour and fill data indicate that net fill is currently occurring in the Ngarradj catchment (table 18). This is contrary to the cross-sectional data in table 11 and is partly a result of the small number of scour chains on Tributary Central (n=3) in comparison to the cross sections (n=15). However, scour and fill only measure net changes in bed levels whereas the data used to compile Table 11 are based on the whole cross section (bed and banks). Therefore, it is possible to determine different trends from the two data sets because of differences between bank and bed processes and their rates. As emphasised in Section 5.2, lateral migration is currently an active but variable process on Tributary Central which cannot be detected by scour chains. Therefore, Table 11 is a more accurate summary of sediment erosion and deposition within the channels in the Ngarradj catchment between 1998 and 2003.

Reach	Mass of sediment (tonnes) stored or eroded						
	1998/1999	1999/2000	2000/2001	2001/2002	2002/2003		
Tributary North	Not installed	20	-20	-48	51		
Tributary Central	Insufficient data	-7	99	-7	12		
East Tributary gauge	3	-3	0	3	5		
Upper Swift Creek gauge	22	3	2	1	4		
Swift Creek gauge	18	5	0	Insufficient data	-7		
Average	43	18	81	-51	65		

 Table 18
 Mass of sediment (tonnes) stored in channel bed in measurement reaches (+ values) or scoured from the bed (- values). Note that the sign is the opposite of that used in table 11 to be consistent with the scour and fill literature

10 Conclusions and recommendations

A total of 56 permanently marked cross sections was installed in the Ngarradj catchment in 1998 and 1999 following the Vigil Network method of the US Geological Survey which was developed for the International Hydrological Decade. The sections have been surveyed during each dry season between 1998 and 2003 to determine the impact, if any, of the Jabiluka mine on large-scale channel changes and sediment storage in the Ngarradj catchment. The program includes two monitoring reaches at gauging stations (East Tributary and upper Swift Creek) on channels not impacted by the mine (multiple controls), two tributaries (Tributaries North and Central) draining the mine site (impact sites) and another impact reach at a gauging station on Ngarradj (Swift Creek) downstream of the two mine site tributaries and the two controls.

The cross section data for the first six years of the project indicate that:

• downstream of the mine, the Floodout Reach of Tributary North is currently stable and is not storing substantial amounts of recently supplied sediment, as often occurs in floodouts. Accelerated sand supply from the mine site has not been recorded to date. The Gullied Reach which is integrated with the Ngarradj channel is developing by the upstream migration of the primary nickpoint and subsequent channel widening and degradation. These geomorphic processes were occurring before the development of the Jabiluka mine and their rates of activity have not been accelerated, since the mine site was developed.

- channel erosion by lateral migration, bed degradation and channel widening are active on Tributary Central. These recent channel changes were initiated between 1950 and 1964, and rapidly developed up to 1975. The above geomorphic processes were not initiated by the Jabiluka mine.
- The percentage changes in hydraulic geometry parameters since 1998 at the East Tributary gauge are much less than on the mine site tributaries, because of the stabilising effects of the monsoonal gallery forest.
- The upper Swift Creek gauge is currently aggrading due to the supply of sand from the upstream catchment, probably from a combination of channel erosion and soil erosion of episodically burnt areas.
- The cross section surveys at the Swift Creek gauge indicate that there has been general bed aggradation since 1998. This sand has been mainly supplied from the upper catchment because the sand from Tributary Central is completely stored before reaching Ngarradj and because Tributary North only supplies small volumes of sand to Ngarradj.

The influence of mean bankfull flow velocity, discharge and specific stream power between 1998 and 2003 on percentage change in bankfull channel geometry parameters over the same period in each study reach was assessed by determining product moment correlation coefficients between these two variables. It was found that:

- There were no significant correlations for the Tributary North main gully and upper Swift Creek gauge.
- Percentage change in area, width and maximum depth were significantly correlated with mean bankfull flow velocity and specific stream power on the Tributary North tributary gully. The first two were negatively and the last one, positively correlated. The reason for the inverse relationship between percentage change in area and width, and the mean hydraulic parameters is that unstable sites were those with the smallest area and width that were undergoing active enlargement and widening near the primary nickpoint whereas enlarged cross sections further downstream were stable. The positive correlation between percentage change in maximum depth and mean bankfull flow velocity and specific stream power indicated that the greatest thalweg scour occurred at sites of largest hydraulic stress.
- There was only one significant correlation (percentage change in area and mean bankfull discharge) on Tributary Central because the greatest changes were caused by lateral migration and hence the hydraulic control on channel changes was masked by planform influences.
- While there were many significant correlations at the East Tributary gauge, extreme values at both tails of the data unduly influenced the significance of the relationships.
- At the Swift Creek gauge percentage change in maximum depth was positively related to mean bankfull flow velocity and specific stream power. Thalweg scour was closely related to the maximum hydraulic stress.

The survey data was also used to calculate changes in sediment storage for each measurement reach and for all reaches combined for each wet season between 1998 and 2003 as well as for the complete period. The channel network was a net sediment source due mainly to high rates of channel erosion in Tributary Central. However, this sediment is stored upstream of the

Ngarradj main channel. When the Tributary Central erosion masses are subtracted from each measurement reach they alternated between a sediment source and a sediment store over time although the trends were not synchronous between reaches.

A total of 30 scour chains were installed between 1998 and 1999 in the same measurement reaches as used for the cross sections to measure scour and fill between the 1998/1999 and 2003/2003 wet seasons. Scour and fill are active geomorphic processes in the Ngarradj catchment that result in the reworking of the sandy bed sediment. Mean scour ranging from a minimum of -6 ± 25 mm on Tributary North during the 2001/2002 wet season to a maximum of -33 ± 24 mm at the Swift Creek gauge during the 2002/2003 wet season was recorded. Greater values were recorded at individual cross sections. Mean fill ranging from a minimum of 2 ± 14 mm at the East Tributary gauge during the 2000/2001 wet season to a maximum of 142 ± 41 mm at the upper Swift Creek gauge during the 1998/1999 wet season was also recorded. Again greater values were recorded at individual cross sections. Allowing for plus or minus twice the standard error of estimate of the mean, average scour and fill for the scour chains during each wet season in each measurement reach usually overlap with each other. This indicates that mean annual scour and fill are not significantly different. On a catchment scale, fill occurred for all five years. However, the standard error of estimate was large in relation to the mean for all years of measurement. Net scour was recorded in at least one measurement reach for all years, except the first.

Continued annual monitoring of the cross sections and scour chains is recommended while the Jabiluka mine is under long term care and maintenance so as to provide data against which subsequent mine impacts or the success of mine rehabilitation can be determined.

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Appendix A Tributary North Cross Section Plots TN01 to TN13, 1998 to 2003

(Cross sections are presented in downstream sequence. For location of sections, see figure 5.)









Appendix B Tributary Central Cross Section Plots TC11 to TC01, 1998 to 2003

(Cross sections are presented in downstream sequence. For location of sections, see figure 9.)









Figure B.13 Tributary Central Cross Section 3 in the Small Capacity Reach



Figure B.14 Tributary Central Cross Section 2 on a distributary of the main channel in the Small Capacity Reach



Appendix C East Tributary Gauge Cross Section Plots ET01 to ET08, 1998 to 2003

(Cross sections are presented in downstream sequence. For location of sections, see figure 15.)





15

20

Distance (m)

25

Figure C.7 East Tributary Cross Section 7 in the Forested Meandering Reach Figure C.8 East Tributary Cross Section 8 in the Forested Meandering Reach

Distance (m)

Right Bank

- 3 Nov 98

- 17 Aug 99

•11 Sep 00

9 Aug 01

- 14 Aug 03

9 Nov 98

-17 Aug 99

11 Sep 00

11 Sep 01

-7 Jun 02

-14 Aug 03

35

30

5995

-7 Jun 02

5993

Appendix D Upper Swift Creek Gauge Cross Section Plots UM01 to UM07, 1998 to 2003

(Cross sections are presented in downstream sequence. For location of sections, see figure 19.)





Appendix E Swift Creek Gauge Cross Section Plots SM01 to SM08, 1998 to 2003

(Cross sections are presented in downstream sequence. For location of sections, see figure 22.)



