Part 3: Jabiluka

Contents[1]

3.1 Monitoring

KKN 3.1.1 Monitoring during the care and maintenance phase

[1] List of papers grouped by Key Knowledge Need.

Monitoring during the care and maintenance phase at Jabiluka

M Iles

Introduction

The Jabiluka project has now entered a long-term care and maintenance phase. While it was ARRTC's view that ongoing monitoring would be required throughout this period, SSD has wound back all ongoing monitoring such that this is now limited to water chemistry. The biological baseline/monitoring sampling program completed water sampling at the end of the 2003–04 wet season. Fish community results for that wet season were reported in the Supervising Scientist's annual report for 2003–04. Macroinvertebrate samples gathered during the 2003–04 wet season are still to be processed.

Chemical and physical monitoring of Ngarradj (Swift Creek)

Toward the end of 2003, Jabiluka entered a long-term care and maintenance phase. The site poses a very low risk to the environment. Consequently, the Supervising Scientist's water chemistry monitoring program at Ngarradj was reduced to monthly sampling for the 2004–05 wet season, augmented by automatic recordings of turbidity and hydrological data at six-minute intervals. The NT DPIFM resumed the role of performing check monitoring at Ngarradj, also on a monthly basis. These independent programs complement each other, providing approximately fortnightly water sampling and a combined dataset to assess the water quality at Ngarradj. ERA continued to carry out independent monitoring on a weekly basis.

The first water chemistry samples for the Supervising Scientist's 2004–05 wet season surface water monitoring program were collected from the Ngarradj downstream statutory compliance point on 6 January 2005. ERA commenced monitoring at that site on 29 December 2004, the day flow was first observed, and DPIFM commenced monitoring in the second week of January. The last samples were collected from Ngarradj on 10 May 2005, by ERA, shortly before flow ceased.

ERA, SSD and DPIFM data generally agree (table 1) with values and trends similar to those seen in previous years measured again this season. The water quality was very good throughout the season with only one exceedance of the electrical conductivity (EC) and the magnesium guideline (table 1) occurring.

- In early January (SSD data) EC at the downstream site was just above the guideline value. The corresponding EC at the upstream site was of a similar value, indicating that the elevation was part of a natural fluctuation in the system.
- The magnesium concentration exceeded the upper guideline in May (ERA data) just before flow ceased. When the water level in the creek drops toward the end of the season increases in magnesium concentrations occur, particularly at the downstream site, which naturally has higher concentrations than upstream. Therefore, the upper level for magnesium has always been a guideline and not a limit. This trend has been noted in

previous years in Ngarradj and at other creeks in the region (eg Magela and Gulungul Creeks).

All other key indicators remained within limits/guidelines. Uranium remained less than 0.5% of the limit throughout the season (figure 2), similar to previous years (figure 1).

The water quality objectives set to protect the aquatic ecosystems downstream of Jabiluka were achieved providing assurance that the environment remained protected throughout the season.

Table 1 Ngarradj (Swift Creek) 2004–05 wet season water quality upstream and downstream of Jabiluka

Parameter	Guide-line or Limit**	Organisation	Median		Range	
			Upstream	Downstream	Upstream	Downstream
pH	3.9–6.0	SSD/DPIFM	4.9	5.3	4.4 – 5.0	4.3 – 5.8
(field data)		ERA	5.0	5.3	4.7 – 5.8	4.8 – 5.7
EC (µS/cm)	21	SSD/DPIFM	15	16	13 – 24	12 – 24
(field data)		ERA	12	10	9 – 17	8 – 15
Turbidity* (NTU)	–	SSD/DPIFM	0.5	0.8	0.3 – 2.2	0.6– 2.0
		ERA	1.	2.	<1 – 6.	<1 – 7.
NO_3 (as NO_3) (mg/L)	1.26	SSD/DPIFM	<0.02	0.04	n = 1 only	<0.02 – 0.13
		ERA	0.02	0.02	<0.02 – 0.38	<0.02 – 0.31
Sulfate‡ (mg/L)	1.5	SSD/DPIFM	0.4	0.3	0.2 – 1.1	0.1 – 1.4
		ERA	0.3	0.3	0.2 – 1.2	< 0.1 – 1.0
Magnesium‡ (mg/L)	0.76	SSD/DPIFM	0.3	0.4	0.2 – 0.6	0.3 – 0.5
		ERA	0.3	0.4	0.2 – 0.4	0.3 – 0.8
Uranium‡ (µg/L)	6.	SSD/DPIFM	0.007	0.010	0.005 – 0.025	0.006 – 0.019
		ERA	0.011	0.012	<0.005 – 0.029	<0.005 – 0.029

ERA data taken from the ERA Weekly Water Quality Report 5 July 2005; * SSD data laboratory data; pH & EC based on field data – the common measurement to all organisations ‡ dissolved (<0.45 µm); **A compliance limit applies to uranium, management guidelines apply all other parameters shown; ERA data *n* = 20, SSD & DPIFM data *n* = 1 – 8.

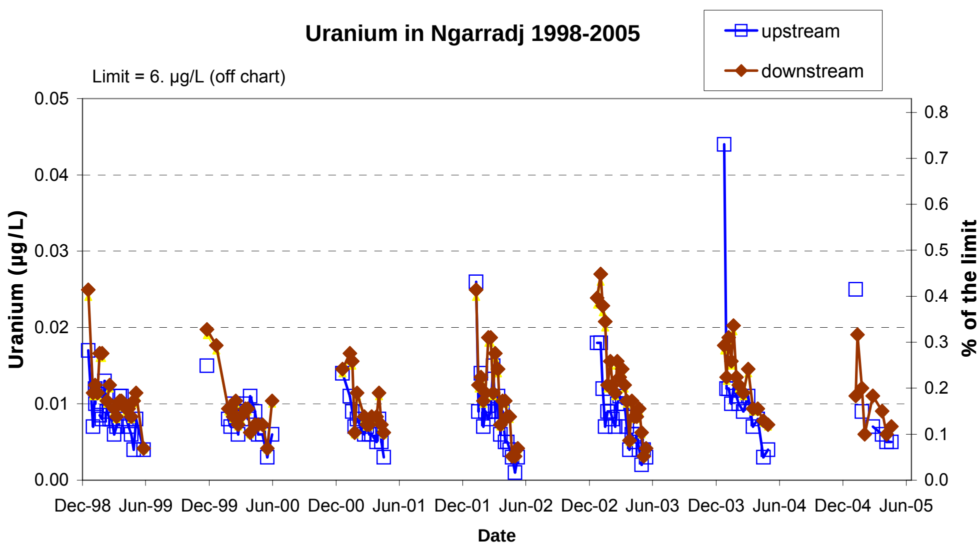

Figure 1 Uranium concentrations in Ngarradj since the 1998–99 wet season (SSD data 1998–99 to 2003–04, SSD & DPIFM data 2004–05)

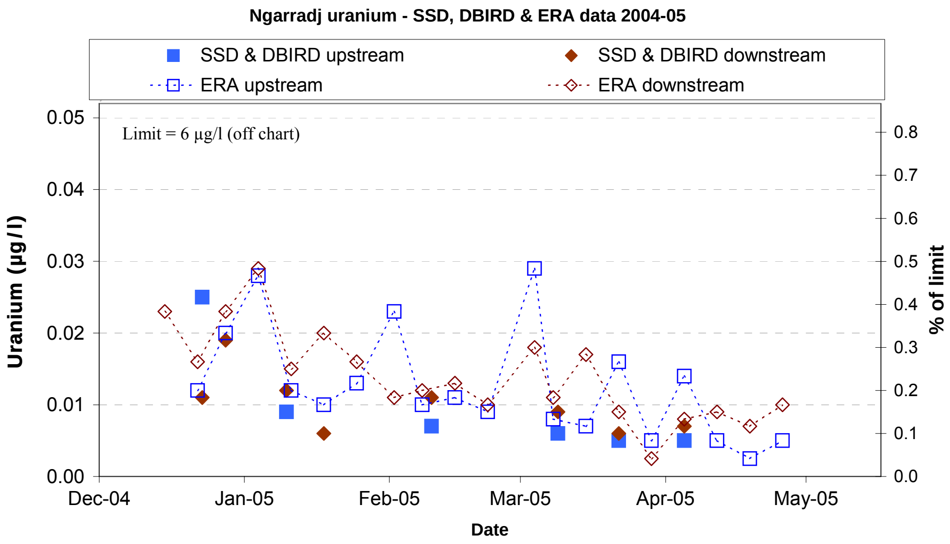

Figure 2 Uranium concentrations measured in Ngarradj by SSD, DPIFM and ERA during the 2004–05 wet season

Monitoring suspended sediment at Jabiluka 1998–2003: establishing baseline

KG Evans, DR Moliere, MJ Saynor, WD Erskine[1] & MG Bellio[2]

Introduction

A stream monitoring program was implemented in the Ngarradj catchment in the late dry season of 1998 and prior to the 1998–1999 wet season principally to assess geomorphic change in streams in the project site catchment and to obtain data to derive erosion model parameters (Erskine et al 2001). Rainfall, stream fine suspended sediment concentration [FSS][3], suspended bedload, solutes, EC, turbidity and stream discharge data were collected for four wet seasons (1998–2002). The data have also allowed (1) determination of baseline characteristics for the measured parameters in the catchment and (2) assessment of impact on water quality resulting from construction of the Jabiluka project site.

Methods

Three river gauging stations were installed in Ngarradj (fig 1 in Saynor et al 2006) prior to the 1998–1999 wet season (Erskine et al 2001): (1) on the unimpacted main channel upstream of the Jabiluka project site UM); (2) on the unimpacted East Tributary channel upstream of the confluence with the main channel (ET); and (3) on the main channel downstream of the project site and the major and minor tributaries (SC) and collected JML data. Changes in the western part of the catchment where the project is located should be seen downstream at SC, through comparison with the upstream ET and UM data.

The Australian and New Zealand water quality guidelines (WQG) (ANZECC & ARMCANZ 2000) were used to determine numerical parameter values for SC which when exceeded will trigger a management response. Two methods were used: (1) comparison of the downstream SC site with percentile limits at the upstream UM site, and (2) a before-after-control-impact, paired difference design (BACIP) where the upstream site UM is before impact in a spatial sense and the downstream site SC is after impact in a spatial sense (Evans et al 2004). In both cases the ET site can be used to confirm whether an observed elevated measurement at SC not observed at UM is (1) from the project-site catchment or (2) from ET and therefore a natural occurrence (eg fig 1). If elevated values are not observed at ET it is assumed that the source is from the project-site catchment.

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3 [FSS] is fine suspended-sediment concentration and comprises the mud [(silt + clay) < 63 μm > 0.45 μm] component of stream sediment.

Results

Upstream limits

Where data are not normally distributed, the WQG recommend a trigger value of the 80^{th} percentile of parameter values of a suitable reference site. In this case the reference site of the downstream site, SC, is the upstream site, UM. Therefore, values measured at SC should be lower than the 80^{th} percentile at UM. Proposed trigger values are, 80^{th}, 95^{th} and 99.7^{th} percentiles representing different levels of interventions by supervising authorities and the stakeholders. The levels of intervention are still under discussion.

The trigger values for SC have been determined using the complete dataset from four years of monitoring (table 1). In the example given (fig 1), a number of SC data points are above the trigger levels. This is due to event related variability.

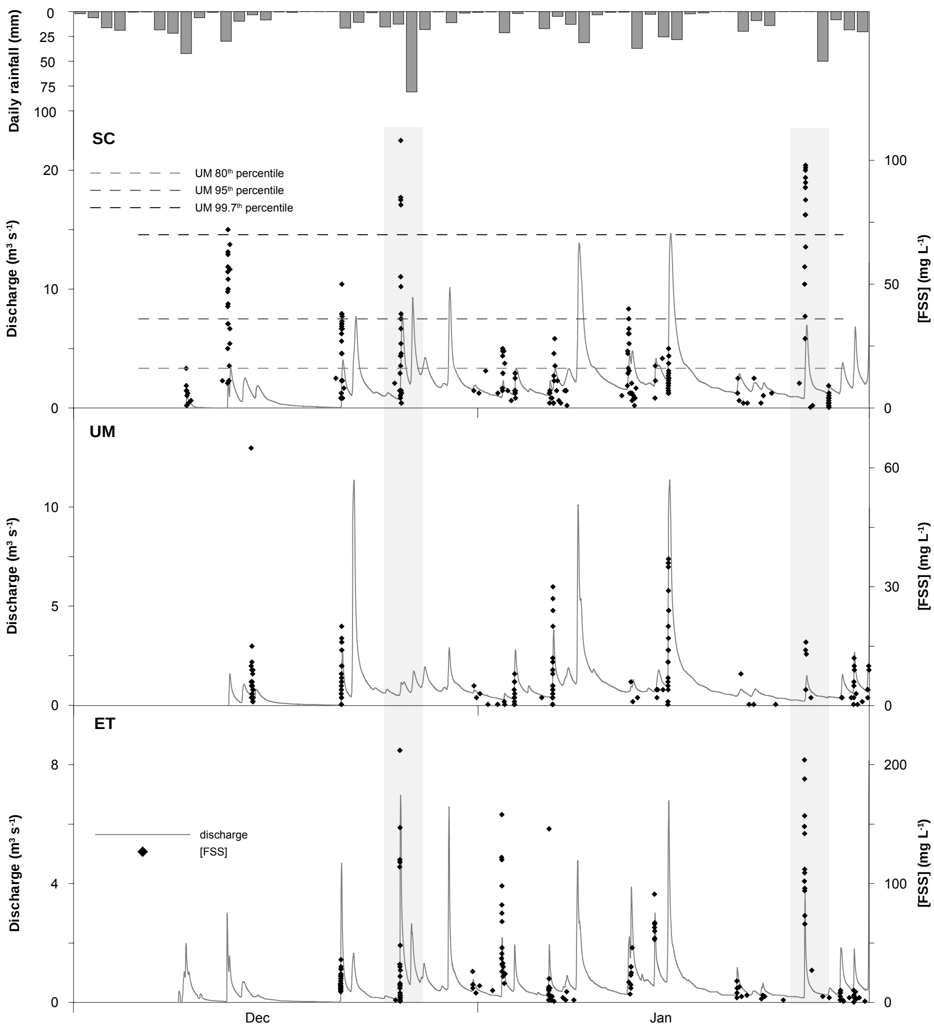

Figure 1 Extract of [FSS] data shows elevated concentrations on 26 December 1998 and 26 January 1999 (shaded regions) at SC and ET but not at UM. [FSS] is fine suspended-sediment, ie the silt + clay fraction (<63 μm >0.45 μm diameter).

Table 1 Trigger values for the downstream SC site derived using the upstream UM reference site

Percentile	Suspended bedload (mg L^{-1})	Suspended mud (mg L^{-1})	Solutes (mg L^{-1})	EC (µS cm^{-1})	Turbidity (NTU)
80	78	16	28	14.1	12
95	151	36	41	17.4	24
99.7	325	70	71	24.3	49

BACIP

UM and SC are treated as paired sites. The time period chosen for comparison was one calendar month. The parameter used to assess impact was the monthly median ($\tilde{\mu}$) parameter value at UM and SC because distributions were generally skewed. The test parameter used was the difference between the median concentration at SC and UM ($\theta_{SC} - \theta_{UM}$). Power analysis indicates that for the number of samples available in this study for an effect size of one standard deviation from the mean, the probability of a Type II (β) error with alpha of 0.05 is 0.20 with a power of 80%.

Since the distribution of the population of $\theta_{SC} - \theta_{UM}$ is normal, trigger values were set as +1σ, +2σ and +3σ respectively. Figure 2 shows $\tilde{\mu}$ for UM and SC and $\theta_{SC} - \theta_{UM}$ for [FSS] and trigger values. Outliers usually result from first flush, fire-impacted events at the start of the 1998–1999 wet season and the 2001–2002 wet season. $\theta_{SC} - \theta_{UM}$ occasionally exceeds +1σ but rarely exceeds +2σ. Values exceeding +2σ are infrequent and irregular and probably result from rainfall and hydrograph variation as expected in this variable natural system.

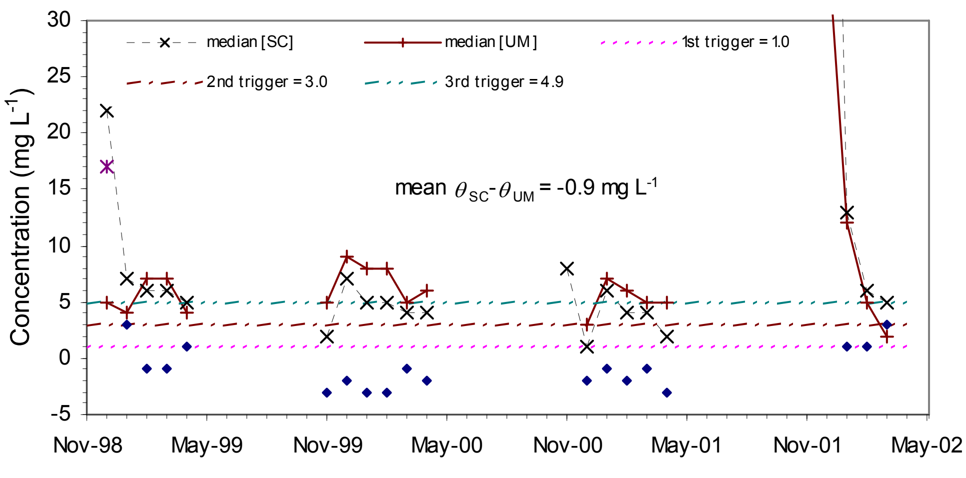

Figure 2 Temporal variation of $\theta_{SC} - \theta_{UM}$ for [FSS] and 1st, 2nd and 3rd order trigger values. Monthly median values for UM and SC are also shown.

Conclusions

The four years of monitoring have provided a high-resolution data set that is almost continuous. The system has high natural variability dependent on rainfall event and subsequent discharge and pre-wet season fire distribution and intensity. In general, parameter values are elevated at the commencement of the wet season until about February. This is caused by first-flush and early wet season removal of surface material detached during the dry season by agents such as bioturbation (including anthropogenic activity), wind erosion and surface desiccation. The analyses showed no observable impact from project construction in 1998 or during the study period. The impacts of dry season fires could be clearly seen. The data set provides good baseline information for future assessment at Jabiluka and demonstrates the need to view measured parameter values on a catchment-wide basis with knowledge of rainfall, discharge and fire distribution. Monitoring data collected during 2002–03 showed no measurable impact on the catchment as a result of the mine (Moliere et al 2003).

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Monitoring suspended sediment at Jabiluka: 2003–2005

DR Moliere, MJ Saynor & KG Evans

Introduction

The Jabiluka uranium deposit is located in the catchment of Ngarradj in the wet-dry tropics of the Northern Territory, Australia (see fig 1 in 'Baseline stream channel stability characteristics in the Ngarradj catchment' in Saynor et al 2006). The Ngarradj catchment will be the first to be affected should any impact occur as a result of mining operations at Jabiluka. In 1998 a stream gauging network was established to determine the pre-mining hydrological and suspended sediment transport characteristics of the Ngarradj catchment. Stream gauging stations were installed upstream (Upper Main – UM; East Tributary – ET) and downstream (Swift Creek – SC) (fig 1) of Jabiluka (Erskine et al 2001).

Since the 2003–04 wet season, data collection has been scaled down within the Ngarradj catchment and only rainfall, discharge and fine suspended-sediment concentration [FSS] data are being collected. During five years of monitoring at Ngarradj between 1998 and 2003, stream suspended-sediment concentration was determined by collecting water samples during the annual hydrograph and filtering and drying the samples in the laboratory (Erskine et al 2001, Evans et al 2004). The collection of water samples and the subsequent laboratory process was very labour intensive and expensive, particularly for monitoring fine suspended-sediment movement over the long term (ie an entire wet season). An investigation was conducted to implement continuous monitoring of turbidity in streams as an indirect measure of suspended sediment concentration.

Progress to date

Detailed turbidity data were collected at the three gauging stations within the Ngarradj catchment (SC, UM and ET) during the 2003–04 wet season using turbidimeters installed at each station. In order to calibrate the turbidimeters to measure [FSS], water samples were collected by the automatic pump samplers for a range of flow conditions and analysed for [FSS]. Significant relationships were fitted between turbidity and [FSS] data for each station (the fitted relationship for SC is shown in figure 1), which showed that the use of turbidimeters is a robust and efficient technique to monitor mud movement within the Ngarradj catchment (Moliere et al 2005a). However, water samples will continue to be collected over several wet seasons to validate or refine the turbidity-[FSS] relationship.

As discussed above, Evans et al (2004) derived numerical trigger values for impact assessment using [FSS] data determined by collecting water samples throughout the event hydrograph and filtering and drying the samples in the laboratory. The parameter used to assess impact within BACIP was the monthly median [FSS] value at each site and it is considered that these trigger values cannot be simply applied to the continuous [FSS] data collected by the turbidimeter. This is because the [FSS] data used to derive the trigger values were collected almost entirely during runoff events and only very few data were collected during baseflow conditions.

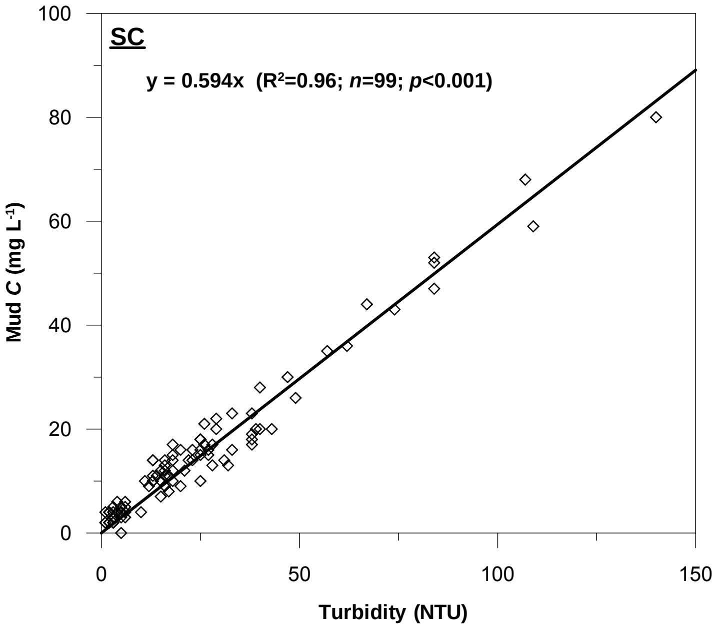

Figure 1 Fitted relationship between turbidity and mud concentration at SC using 2003–04 data

The continuous turbidity data were collected throughout the entire annual hydrograph (ie during both runoff events and baseflow conditions). Therefore, the monthly median [FSS] values for the two datasets cannot be compared. As a result, a variation of the BACIP analysis previously done by Evans et al (2004) was derived by Moliere et al (2005b) for impact assessment using event mud (fine suspended-sediment) loads derived from [FSS] data collected by the turbidimeter. This assessment uses an event-based BACIP design where SC and the combination of UM and ET are treated as paired sites and the comparison of ratios is used to assess impact. Therefore, only events where event loads were determined for all three stations were used in the analysis.

Figure 2 shows that the mean ratio of UM + ET mud load to SC mud load for the two-year monitoring period (2003–04 and 2004–05) is approximately one. The events of 'interest' are those that lie greater than one standard deviation below the mean ratio (ie <-1 SD) because these are events where elevated mud loads are measured downstream of Jabiluka at SC relative to the upstream combined load at UM and ET. For example, during 2004–05 there were two events below the -1 SD line (fig 2) and these were associated with the high magnitude events on 2–4 February discussed in Moliere et al (2005b). Nevertheless, the event-based BACIP analysis indicates that the ratios of event mud load observed at UM and ET to SC during these two events are not considered as outliers as they are within the 95% prediction intervals (ie within two standard deviations) of the mean ratio.

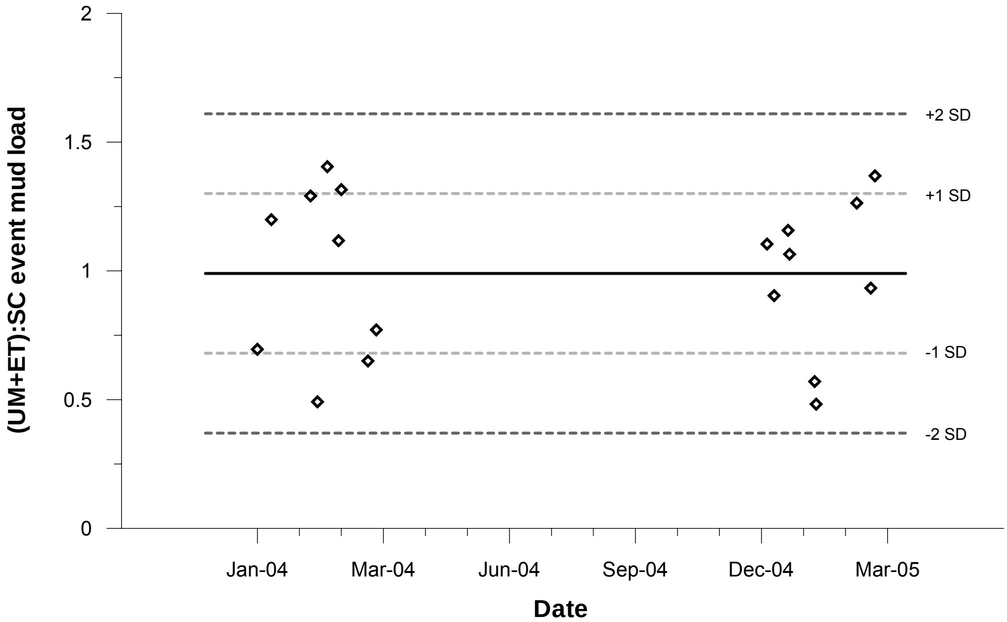

Figure 2 Temporal variation of the ratio of event mud loads measured at UM and ET to that at SC during 2003–04 and 2004–05 (indicated as ◇). The mean ratio and associated standard deviations are also shown.

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Baseline stream channel stability characteristics in the Ngarradj catchment

MJ Saynor, WD Erskine[1], DR Moliere & KG Evans

Introduction

In 1998, ***eriss*** installed three river gauging stations, two upstream (Upper Main – UM; East Tributary – ET) and one downstream (Swift Creek – SC) (figure 1) of the Jabiluka project area to monitor hydrology and suspended sediment transport within the Ngarradj catchment. At each station, rainfall, streamflow and suspended sediment concentration data were collected throughout the wet season. In addition, numerous cross sections, scour chains and erosion pins were installed along the main channel and several tributaries within the Ngarradj catchment to determine the channel stability and geomorphological characteristics of the catchment and any changes that may occur as a result of project area disturbance (Erskine et al 2001, Saynor et al 2004a).

Results

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. Cross section and scour chain measurements were conducted between late 1998 and 2003 when rainfall was at or above average. 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 (September to August, inclusive) were 13, 71, 21, 2 and 9 years respectively.

The seasonal streams gauged by ***eriss*** commenced flowing on 8 November (1999) at the earliest (streamflow did not persist after this first flush and recommenced on 20 November 1999) but usually on or after 20 November each year. The amount of rainfall before streamflow commenced varied between 225 and 440 mm. Streamflow generally persisted until between May and July each year, depending on the amount of wet season rainfall. The largest peak instantaneous discharges were recorded during the 1998/1999 wet season but the variation between years was minor, as was the variation in maximum flow velocity between years (Saynor et al 2004a).

A total of 56 permanently monumented channel cross sections were surveyed during each dry season between 1998 and 2004. In most surveyed river reaches the channels are reasonably stable apart from active nickpoint retreat on Tributary North and channel erosion by lateral migration, bed degradation and channel widening on Tributary Central (Saynor et al 2004a, 2006a). Aerial photograph interpretation showed that these geomorphic processes were occurring before the construction of the Jabiluka project and their rates of activity have not accelerated since the project site was developed.

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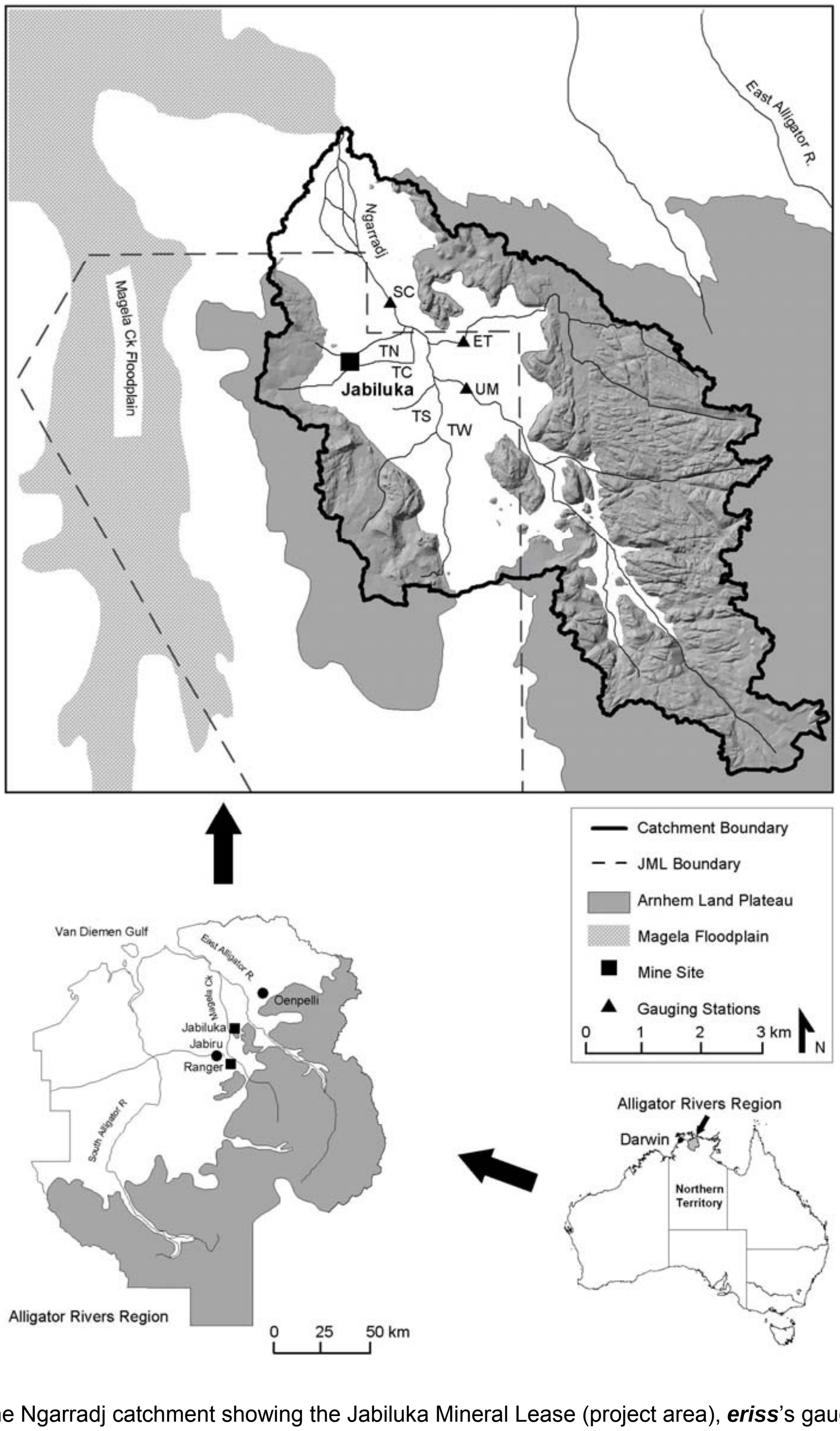

Figure 1 The Ngarradj catchment showing the Jabiluka Mineral Lease (project area), ***eriss***'s gauging stations and local creek names. SC refers to Swift Creek gauging station, TN Tributary North, ET East Tributary gauging station, TC Tributary Central, TS Tributary South, TW Tributary West and UM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

A total of 30 scour chains were installed on some of the surveyed cross sections to measure scour and fill during wet season floods. Scour and fill are active geomorphic processes in the Ngarradj catchment that result in the reworking of the sandy bed sediment. Mean scour and fill rates were determined for each reach for each wet season. 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 overlapped with each other (Saynor et al 2004a, 2006b). This indicates that mean annual scour and fill are not significantly different between reaches.

Bed material samples were also collected at each of the 56 cross sections during each dry season between 1998 and 2004. Particle size analysis was completed on all of these samples and graphic grain statistics were calculated. Statistical analyses of the grain size statistics showed that any annual changes at the sites downstream of the project area also occurred synchronously at the sites upstream of the project area (Saynor et al 2006c). The grain size statistics data constitute thorough baseline information for the Ngarradj catchment and can now be used to determine any subsequent changes due to future activities in the project site.

Up to four years of erosion pin measurements in the Ngarradj catchment have established that substantial bank erosion (up to 285 t/a) has occurred during the wet season on the project area tributaries by rapid lateral migration (Tributary Central) and by erosion of gully sidewalls due to a combination of within-gully flows and overland flow plunging over the sidewalls (Tributary North) (Saynor et al 2003, 2004b, Saynor & Erskine 2006). Bank erosion also occurred during the dry season by faunal activity, by desiccation and loss of cohesion of the sandy sediments, and by dry flow processes but at very low rates. Channels with dense riparian vegetation did not generate significant amounts of sediment by bank erosion. Deposition was also locally significant, despite the sandy bank sediments. Bank profile form and channel planform exert a strong control on erosion rates during the wet but not during the dry season (Saynor & Erskine 2006).

Discussion

Work on bedload flux and a sediment budget will be finalised during 2005–2006. This will complete the assessment of stream channel characteristics of the Ngarradj ctachment. Even prior to the completition of this last project, sufficient information has now been collected on channel stability of the Ngarradj catchment to reliably determine whether any geomorphic changes occur in the future. The results of this study show that the gemorphic processes operating in the Ngarradj catchment have not been impacted on or accelerated as a result of the construction of the project area at Jabiluka, although the wet season rainfall has generally been above average.

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Gully initiation near the Jabiluka project area

MJ Saynor, WD Erskine[1], KG Evans & I Eliot[2]

Introduction

This research assesses the significance of vehicular traffic as a major process of gully initiation on the sandy footslopes below the Jabiluka project area. Duggan (1988) found that gullies up to 1 m deep have formed during one wet season on disturbed slopes <2° in the seasonally wet tropics of the Kakadu region. Vehicular traffic and cattle and buffalo tracks damage vegetation and destroy protective gravel lags causing gully development (Williams 1976, Duggan 1988, Skeat et al 1996, Saynor et al 2006). The area surrounding the Jabiluka project area exhibits very shallow sands on steep slopes, shallow red or brown uniform sands at the base of bedrock outcrops and deep uniform sands on the footslopes (Bettenay et al 1981). Channels draining the Jabiluka project site are discontinuous, unstable, seasonal streams, devoid of riparian forest (Erskine et al 2001). Gully erosion occurs by nickpoint initiation, upstream nickpoint retreat and subsequent bank erosion of the incised sections (Erskine et al 2001). The studied chanel, Tributary North (fig 1), now has an extensive gully network immediately upstream of the confluence with the main stream, Ngarradj.

Results

Air photograph interpretation showed vehicular track development between 1964 and 1975 through a vegetated swale that then characterised Tributary North. Flow concentration and soil disturbance in wheel ruts caused localised erosion which developed into two gullies (fig 1) after 1982. Erosion had caused the realignment of the track by 1984 and by 1987 gully 1 (fig 1) had formed an integrated channel with Ngarradj. Another track developed in 1998 and, if left unrepaired, may have also initiated gullying where the surficial root mat had been disturbed in a number of severely burnt areas. However, since 1998, track use has been infrequent. In September 1998, an intense fire burnt 10.2 km^2 of the Ngarradj catchment and most of the Tributary North catchment.

The 1998 track was observed immediately after the 1998/1999 wet season (rainfall of 1914 mm). A series of flow-aligned scour holes (Scott & Erskine 1994) had formed in the wheel ruts at two locations on the track. Five holes in the left rut were clustered with two holes in the right rut in a downstream zone 29 m long and another four holes were clustered in the left rut further upstream in a zone 9.5 m long. Approximately 1 m^3 (1.49 t) of sediment was eroded along a distance of 40 m. During the 1999/2000 (rainfall of 2047 mm) and the 2000/2001 wet seasons (rainfall of 1897 mm), the scour holes remained stable following grass colonization. To ascertain why scour hole erosion was initiated on the track rather than elsewhere in grassed depressions, soil characteristics of the track and adjacent areas to a depth of 125 mm were determined (Saynor et al 2004).

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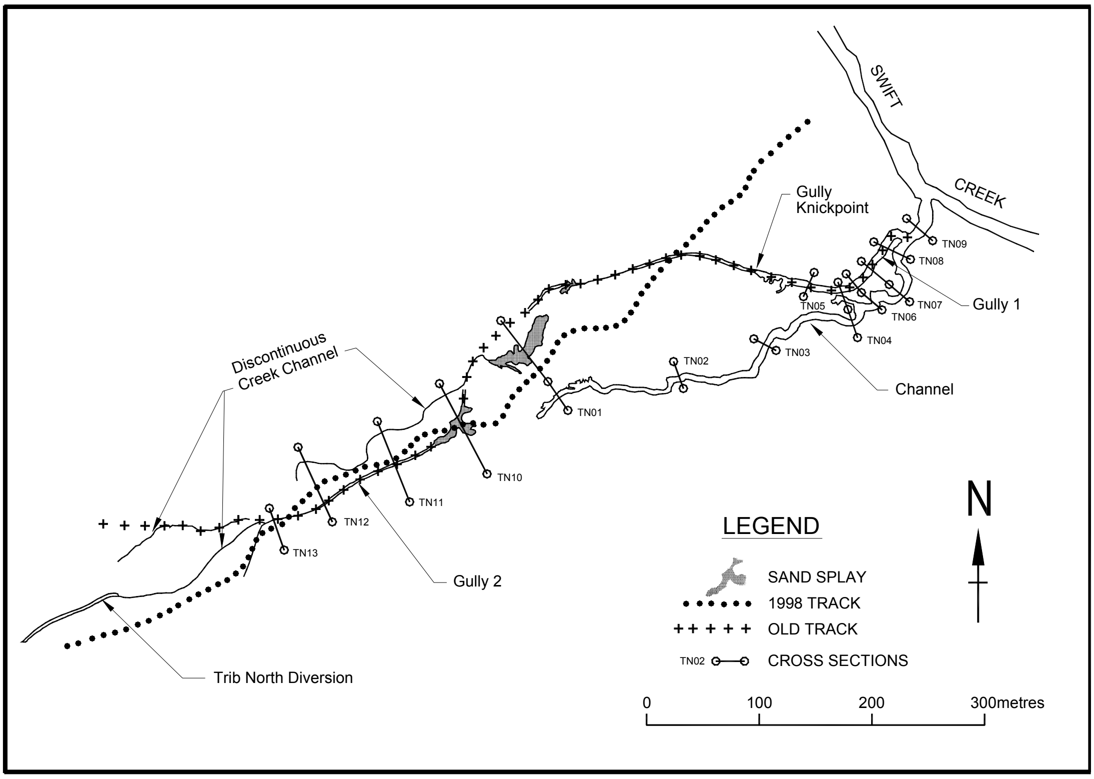

Figure 1 Tributary North showing surveyed tracks, gullies, sand splays and cross sections

The soils are uniformly coarse textured arenic rudosols (Isbell 1996) exhibiting minimal development of a weakly coherent, sandy A_1 horizon over more than 1 m of sandy regolith (C horizon). Roots were common in the A_1 horizon but not at depth. Mean loss on ignition of track surface soils (0–50 mm) was not significantly different from the unburnt areas (ρ = 0.97) but both burnt and unburnt surficial soils exhibited higher mean loss on ignition than the subsurface soils (75–125 mm) ($0.045 > \rho > 0.0012$). Mean bulk density of track surface soil was significantly greater than both unburnt surface soil (ρ = 0.001) and unburnt subsurface soil (ρ = 0.022) indicating that limited traffic on these sandy soils had significantly increased surficial soil bulk density. Mean root percentages were significantly different between road track surface and undisturbed surface soil ($\rho < 0.05$), indicating that multiple vehicle passes had pulverized and compacted the surficial soil partially breaking down the root mat that was subsequently removed by wet season overland flows.

Discussion and conclusions

Root and algal mats increase soil cohesion, limiting wash erosion and channel incision, and grass vegetation increases critical boundary shear stress for soil erosion (Prosser et al 1995). Vehicular traffic can increase compaction and subsequent erosion rates overriding the effect of erosion-reducing factors (Evans & Loch 1996). The lack of erosion of the scour holes during the wetter 1999/2000 wet season indicated that the combined disturbances of fire and root breaching by vehicles were more important in causing erosion than the amount of overland flow. The coarser sand on the track also predisposed it to erosion when multiple vehicle passes compacted the soil and disturbed the root and algal mats.

Coalescence of the discontinuous scour holes into a gully during subsequent wet seasons did not occur because:

1 vehicles avoided the eroded section and used a new track alignment;

2 grasses regenerated during the wet season following scour hole initiation, re-establishing root and algal mats;

3 an intense, late dry season fire burnt the grassed swales prior to 1998/1999 wet season, before the track was used repeatedly and removed all above ground cover before the first vehicle passes. As a result, vehicles caused greater disruption of the root and algal mats than would have occurred if the grass cover had not been burnt. A similar intensity late season fire has not occurred since the track was formed;

4 the grassed swales are not part of the main channel network and hence only convey episodic overland flows; and

5 vehicular traffic in the area has been greatly reduced since the scour holes were initiated.

The developmental sequence of a gully from a grassed swale via scour holes is reversible. As outlined in figure 2, scour holes can be converted back to grassed swales, provided the process disturbing the grass cover and root and algal mats is quickly identified and removed. The abandonment of the eroded section of the track and the renewed growth of grass during the next two wet seasons resulted in some infilling of the scour holes.

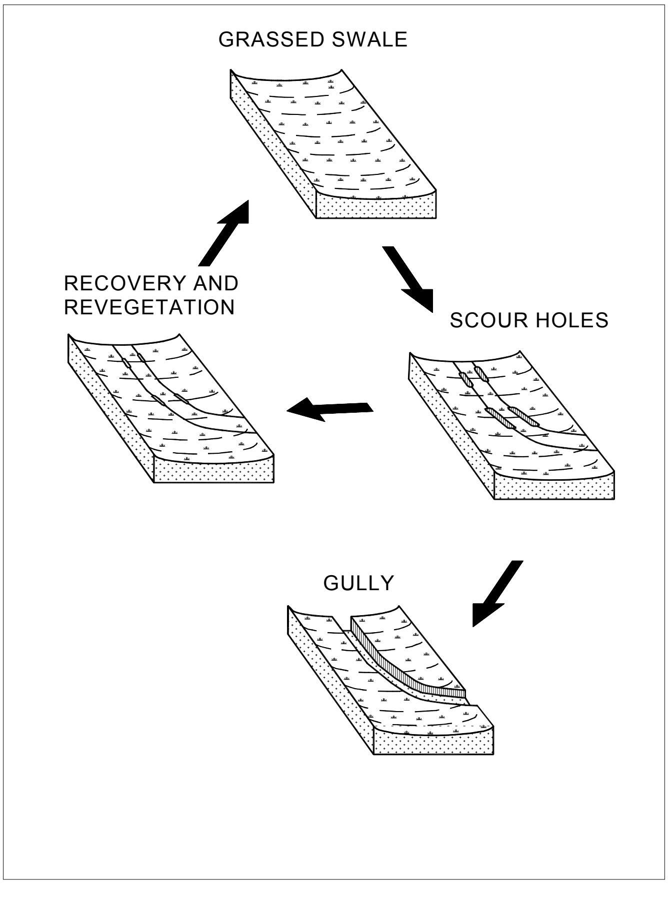

Figure 2 Gully development in grass swales involving a reversible intermediate stage for scour holes

Scour holes are the initial phase of gully development and should be identified and treated before large scale erosion occurs. Gully erosion prevention is better than cure because the greatest sediment yields are generated during the initial growth stage (Graf 1977, Prosser & Winchester 1996, Erskine 2005).

The progression of disconnected scour holes to gullies can be prevented by stopping the continued disturbance of the root and algal mats and by re-establishing the grass cover. The recognition of scour holes as an intermediate step in the development of a gully allows their targetting with soil conservation works and their reversion to a grassed swale. Traffic should also be restricted on sensitive landforms to prevent localised erosion (Evans & Loch 1996).

Acknowledgments

Michael Grabham, Dr Guy Boggs, Dr Max Finlayson, Bryan Smith and Gary Fox are thanked for their contributions.

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Scour and fill in the Ngarradj catchment between 1998 and 2003

MJ Saynor, WD Erskine[1] & KG Evans

Introduction

Two fluvial processes, bank erosion and bed scour and fill, were identified as significant sediment sources during initial field inspections of the Ngarradj catchment before construction of the Jabiluka project area (Erskine et al 2001). Bed scour and fill are discussed in this paper. Actual depths of bed scour and fill during wet season floods are usually much greater than the net changes in bed level measured at the permanently monumented cross sections between successive dry season, discussed by Saynor et al (2006) in this volume. 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. The study area characteristics and hydrology are outlined in Saynor et al (2006) in this volume and the location of the study area is shown in figure 1 of Saynor et al (2006). The aim of the work was to determine the amount of scour and fill in the sand-bed streams in the Jabiluka project area.

Methods

Depths of scour and fill during each wet season between 1998 and 2003 were measured by metal scour chains, as developed by Emmett and Leopold (1963), Emmett (1965) and Leopold et al (1966). Thirty scour chains were installed in various channel reaches of the Ngarradj catchment during the late dry seasons of 1998 and 1999. The scour chains were always located on surveyed cross sections to aid recovery (Saynor et al 2001; 2004). The chains were installed so that the top link of the metal chain was level with the channel bed. After each wet season the elevation of the stream bed was resurveyed before the bed was excavated until the chain was exposed. Various measurements were made between the dry season bed level and the scour chain, which were then used to determine the amount of scour and fill that occurred in the previous wet season (Saynor et al 2004). Figure 1 shows the three examples of bed level change that can occur during a wet season. Depth to straightened chain (DSC) is one of the measurements made and is the actual change in bed level between successive dry seasons.

Scour chain results

Data for the scour chain measurements are contained in Saynor et al (2002, 2004a) and detailed results are contained in Saynor et al (2004b). Table 1 shows the average values of net change in scour and fill for each study reach in the Ngarradj catchment for each year of measurement. Net scour is denoted by a negative value and net fill by a positive value.

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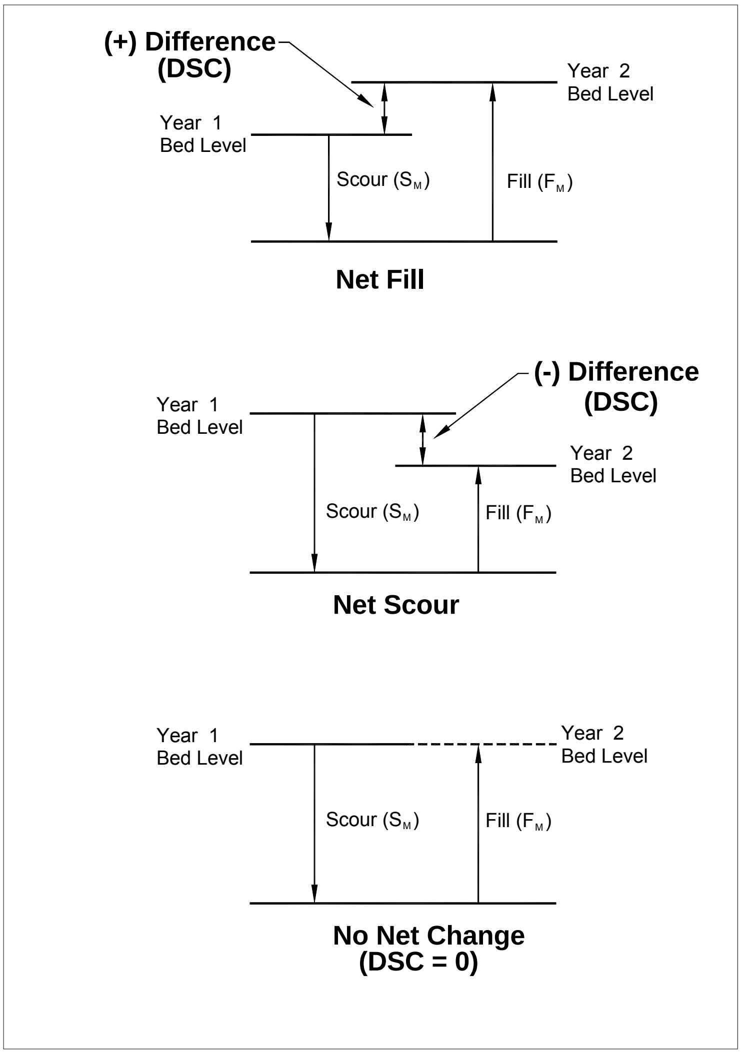

Figure 1 Three examples of net channel bed change during the wet season measured by scour chains. Net fill occurs when the bed level for the 2nd year is higher than for the 1st (top). Net scour occurs when the bed level for the 2nd year is lower than for the 1st (middle). No net change occurs when the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

Table 1 Mean net scour (negative) and net fill (positive) and the standard error of estimate for each reach in which scour chain measurements were made for each wet season. All units are in mm. For location of study reaches, see figure 1 in Saynor et al (2006).

Reach	1998/1999 Scour/Fill	1999/2000 Scour/Fill	2000/2001 Scour/Fill	2001/2002 Scour/Fill	2002/2003 Scour/Fill
Tributary North	Not Installed	25 ± 16	-25 ± 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	-33 ± 24
Average	85 ± 28	7 ± 11	18 ± 21	6 ± 8	24 ± 17

Except for the 1998/1999 wet season for which there is the least 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.

The catchment average net scour and fill was calculated as the arithmetic mean of the averages for each measurement reach (table 1). 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 the least data. 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 project area because mine-derived 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. The data in table 1 have been converted to sediment masses in table 2 by using known measurement reach lengths (Saynor et al 2004b) and a uniform sediment bulk density of 1.5 t/m^3. The scour and fill data indicate that net fill is currently occurring in the Ngarradj catchment (table 2).

Table 2 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 1 to be consistent with the scour and fill literature.

Reach	Mass of sediment (tonnes) stored (+) or eroded (-)				
	1998/1999	1999/2000	2000/2001	2001/2002	2002/2003
Tributary North	Not installed	20	-20	-5	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	-2	65

Conclusions

Scour and fill were active geomorphic processes in the Ngarradj catchment between 1998 and 2003 that resulted 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 were 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.

Acknowledgments

Michael Grabham, Dr Guy Boggs, Dr Max Finlayson, Bryan Smith, Gary Fox and Elice Crisp are thanked for their contributions.

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

MJ Saynor, WD Erskine[1] & KG Evans

Introduction

Various fluvial erosion processes were identified as potential sediment sources during initial field inspections of the Ngarradj catchment before construction of the Jabiluka project (Erskine et al 2001). Two of these processes were bank erosion and scour and fill of the sandy creek beds. This paper documents the study of channel change and large-scale bank erosion. To measure the amount of large-scale bank erosion in the Jabiluka project area, permanently marked channel cross sections on the project site tributaries (Tributaries North and Central) and at the three ***eriss*** gauging stations (figure 1 in Saynor et al 2006) were installed. Erosion pins were used to measure small-scale and slow rates of bank erosion in the Ngarradj catchment (Saynor et al 2003, Saynor & Erskine 2006). The study area characteristics and hydrology are outlined in Saynor et al (2006). The aim of the work was to determine changes in channel morphology due to bank erosion in the sand-bed channels on the Jabiluka project area that may be due to project site disturbance.

Methods

Fifty-six permanently monumented channel cross sections were installed throughout the Ngarradj catchment during the 1998 dry season, following the approach of Miller and Leopold (1963) and Leopold et al (1966). Multiple cross sections were installed at each 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 in Saynor et al 2006). Site-specific details of the ***eriss*** research program in the Ngarradj catchment are provided by Saynor et al (2001). The cross sections were surveyed annually during each subsequent dry season to 2003 to determine the net change during each intervening wet season. 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) and are discussed in Saynor et al (2006) in this volume. The cross sections were also used to determine bankfull hydraulic geometry parameters (width, mean depth, area, mean velocity, bankfull discharge and specific stream power) for each survey and changes in channel geometry between surveys.

The data for the annual cross section surveys in the Ngarradj catchment between 1998 and 2003 are presented in Saynor et al (2002, 2004a). Figure 1 shows an example of a cross section plot from Ngarradj and all cross section plots are shown in Saynor et al (2004b). Where changes in hydraulic geometry parameters between 1998 and 2003 are less than ± 1%, the section is called stable.

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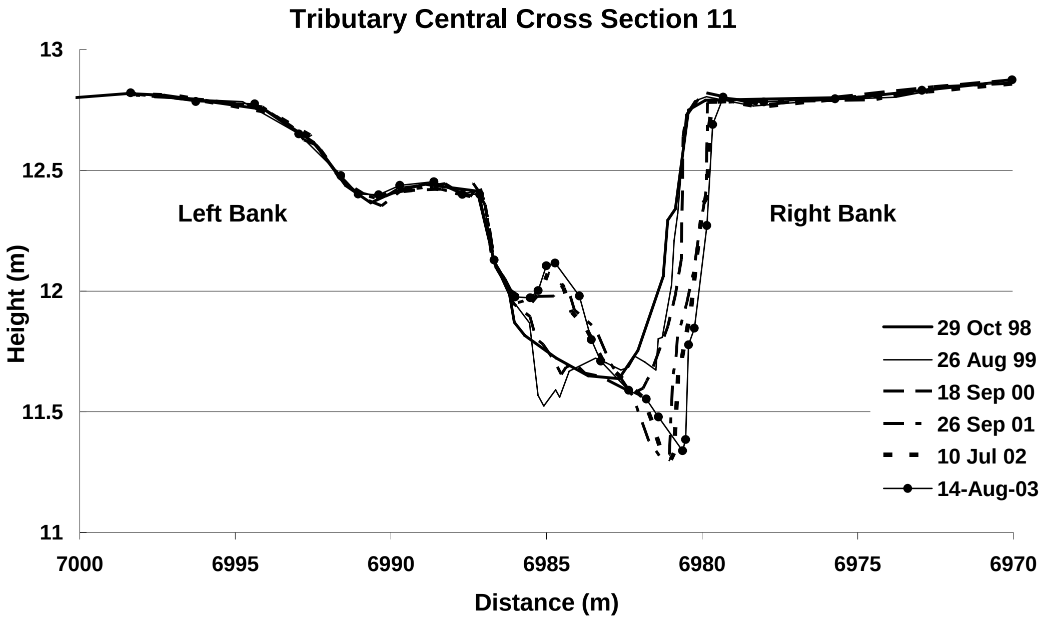

Figure 1 Tributary Central cross section 11

Results and conclusions

Cross section surveys were used to derive the channel hydraulic parameters for each year between 1998 and 2003, and summarised in table 1.

Integrating the data from table 1 for the six years 1998 to 2003 indicates that:

- The lower gullied section of Tributary North which, is integrated with the main Ngarradj channel, is developing by upstream migration of the primary nickpoint and subsequent channel widening and bed degradation. Aerial photograph interpretation (Saynor et al 2004b) indicated that these geomorphic processes were occurring before the development of the Jabiluka project area and their rates of activity have not been accelerated since the project site was developed.
- Channel erosion by lateral migration, bed degradation and channel widening are active on Tributary Central. Air photograph interpretation indicated that these recent channel changes were initiated between 1950 and 1964, and rapidly developed up to 1975 (Saynor et al 2004b). The above geomorphic processes were not initiated by the Jabiluka project area.
- The percentage changes in hydraulic geometry parameters since 1998 at the East Tributary gauge are much less than on the project 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 Swift Creek gauge has also aggraded since 1998. This sand has been mainly supplied from the upper catchment because upper Swift Creek is also aggrading, because the sand from Tributary Central is completely stored before reaching Ngarradj and because Tributary North only supplies small volumes of sand to Ngarradj.

Table 1 Changes in various hydraulic geometry parameters between 1998 and 2003. The percentage value in the brackets indicates the maximum change.

Hydraulic geometry parameter	**Tributary North main gully**	**Tributary North tributary gully**	**Tributary Central**	**East Tributary**	**Upper Swift Creek**	**Swift Creek**
Number of cross sections	8	5	14	8	8	8
Cross-sectional area	Decreased at 3 (3%) Increased at 4 (16%) Stable at 1	Decreased at 2 (5%) Stable at 3	Decreased at 2 (30%) Increased at 11 (46%) Stable at 1	Decreased at 1 (2%) Increased at 7 (12%)	Decreased at 8 (10%)	Decreased at 5 (10%) Stable at 3
Width	Increased at 7 (21%) Stable at 1	Increased at 4 (20%) Decreased at 1 (3%)	Decreased at 3 (10%) Increased at 9 (45%) Stable at 2	Decreased at 1 (2%) Increased at 7 (6%)	Decreased at 1 (3%) Increased at 5 (5%) Stable at 2	Decreased at 1 (4%) Increased at 5 (14%) Stable at 2
Mean depth	Decreased at 6 (6%) Increased at 2 (8%)	Decreased at 5 (15%)	Decreased at 5 (18%) Increased at 5 (23%)	Decreased at 2 (4%) Increased at 5 (9%) Stable at 1	Decreased at 8 (11%)	Decreased at 6 (17%) Increased at 1 (1.1%) Stable at 1
Maximum depth	Increased at 7 (31%) Stable at 1	Decreased at 4 (10%) Stable at 1	Decreased at 3 (4%) Increased at 11 (38%)	Decreased at 1 (17%) Increased at 6 (25%) Stable at 1	Decreased at 8 (14%)	Decreased at 7 (17%) Increased at 1 (3%)
Mean velocity	Decreased at 4 (2.8) Increased at 2 (4.7%) Stable at 1	Decreased at 5 (12%)	Decreased at 5 (17%) Increased at 7 (13%) Stable at 2	Decreased at 3 (3.5%) Increased at 5 (6.3%)	Decreased at 8 (8.5%)	Decreased at 6 (12%) Increased at 1 (1.3%) Stable at 1
Bankfull discharge	Decreased at 4 (5.3%) Increased at 4 (16%)	Decreased at 5 (11%)	Decreased at 3 (41%) Increased at 11 (565%)	Decreased at 1 5.3%) Increased at 7 (19%)	Decreased at 8 (15%)	Decreased at 7 (18%) Stable at 1
Specific stream power	Decreased at 6 (7%) Increased at 2 (11%)	Decreased at 5 (25%)	Decreased at 5 (36% Increased at 9 (33%)	Decreased at 2 (7.3%) Increased at 5 (17%) Stable at 1	Decreased at 5 (20%) Stable at 3	Decreased at 6 (26%) Increased at 1 (3.1%) Stable at 1

The survey data were 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.

Acknowledgments

Michael Grabham, Dr Guy Boggs, Dr Max Finlayson, Bryan Smith, Gary Fox and Elice Crisp are thanked for their contributions.

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