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Assessment of the off-site geomorphic impacts of uranium mining on Magela Creek, Northern Territory, Australia

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supervising scientist

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Summary

The aim of this report was to complete the following three tasks from a review of the relevant literature and from the authors' field work in the Alligator Rivers region and past experience.

1. Review all of the existing data relevant to the discharge of solutes and particulate material from the rehabilitated mine site at Ranger uranium mine and from nearby tributaries of Magela Creek;
2. Determine the fate of particulates in the off-site system; and
3. Collate and review all of the existing material relevant to an understanding of the long-term behaviour of Magela Creek and its tributaries.

In relation to the first task, rainfall at the Ranger uranium mine is acidic and has a low dissolved solids and nutrient content. Magela Creek water is characterised by very low conductivity and low suspended solids concentrations that exhibit exhaustion as the Wet season progresses. The suspended particulate matter of Magela Creek contained approximately 25% organic matter, 15% iron oxide, and the remainder consisted of varying amounts of clay (predominantly kaolinite with some chlorite), quartz and aluminium oxide. Sediment and solute yields of Magela Creek are less than 11.8 and 2.5 t/km^2 yr, respectively, and are low by world standards. Bedload yield is a relatively high proportion (48.6%) of the total sediment load yield and this occurs at all scales from waste rock dump plots to major rivers in the Alligator Rivers Region. Disturbed sites generate sediment yields that are an order of magnitude higher than those from natural catchments (up to 5100 t/km^2.yr). Large storms dominate soil erosion and sediment transport. Any future climate change due to the enhanced greenhouse effect that increases rainfall intensities and/or storm frequencies will increase soil erosion rates and sediment yields. Up to 7 m of erosion and 20.4 x 10^6 t of sediment will be eroded from the rehabilitated mine site over the 1000 years structural life. Assuming sediment delivery ratios of between 0.24 and 0.50, up to 15.5 x 10^6 t will be stored on the rehabilitated mine site and 10.2 x 10^6 t will be transported off the mine site. Assuming a sediment delivery ratio of 0.28, which was measured for a local catchment in the Alligator Rivers Region, 9.1 x 10^6 t will be stored on the rehabilitated mine site and 3.6 x 10^6 t will be exported. The rehabilitated mine site should be stabilised by revegetation, the installation of convexo-concave slope profiles, the spreading of surficial gravel lags and protection of the site from fire.

In relation to the second task, not all of the sediment eroded from the rehabilitated mine site during the 1000 years structural life will be exported off-site. Published empirical relationships of sediment delivery ratios versus catchment area indicate that between 50 and 76 % of the eroded sediment will be retained on the rehabilitated mine site. The most significant sediment storage sites downstream of the mine site will be the mine site tributaries and their associated floodplains and backflow billabongs. It is predicted that between 3.1 and 10.2 x 10^6 t will be exported to the mine site tributaries and that between 3.1 and 7.0 x 10^6 t will be stored there. The backflow billabongs will be completely infilled with mine-derived sediment over the 1000 years structural life of the rehabilitated mine site. For the most likely rehabilitated mine site scenario, 3.6 x 10^6 t will be exported from the rehabilitated mine site to these tributaries and 3.5 x 10^6 t will be stored. Little research has been conducted on the sediment dynamics and storage of these tributaries to date. Relatively minor sediment supply will occur in the anastomosing sand zone of Magela Creek. The lower Magela Creek floodplain is unlikely to receive any mine-site-derived sediment. However, should this occur, essentially all of the mine-derived sediment supplied to the lower floodplain will be trapped.

In relation to the third task, environmental responses to greenhouse-induced climate and sea level changes as well as to longer term hydro-isostatic climate changes are manifested through hydrological, hydrodynamic, geomorphological and ecological processes that interact with each other. Greenhouse-induced climate and sea level changes to the year 2030 are likely to include an increase in storminess due to greater rainfall intensities, more heavy rain events and/or local topographic effects on rainfall, a rise in sea level by between 80 and 300 mm and an increase in temperature by 0.85 to 1.0°C. Increased storminess will cause higher soil and channel erosion rates and hence will increase suspended loads, bedloads and sediment yields. Reductions in wet season vegetative cover and/or increases in dry season fire extent and/or intensity will also cause further increases in sediment yields. Sea level rise will re-establish tidal connection with the old tidal channels and cause extensive salinisation of the most downstream wetlands on Magela Creek. This will cause the remobilisation of stored sediments but a large proportion should be redeposited elsewhere on the floodplain.

A substantial fall in sea level due to the start of the next glacial will result in incision of Magela Creek downstream of the Ranger mine site and the remobilisation of massive amounts of stored sediments and the oxidisation of the remaining sediments. Mine site tributaries will be rejuvenated and any stored mine site generated sediment will be flushed into Magela Creek.

While a disproportionately large effort has been directed at understanding the evolution and behaviour of the sand anastomosing reach and lower floodplain of Magela Creek, these sections will not be the initial repositories for mine-derived sediment. The geomorphic behaviour and sediment dynamics of mine site tributaries are not as well understood but are certainly more important sediment stores and sediment pathways for mine-derived particulates. The reason for this discrepancy in research effort is that the lower Magela wetlands are internationally significant and have, therefore, been perceived as being the most important ecosystem likely to be impacted by mining. Under the most likely post-rehabilitation scenario, no mine site generated particulates will reach the lower Magela wetlands. Additional hydrological, geomorphic and limnological monitoring of mine site tributaries and backflow billabongs is recommended.

It is essential that the probability and magnitude of extreme storms and floods are more accurately defined because of their potential significance for soil erosion, sediment transport, channel changes and avulsions, and landform evolution modelling by SIBERIA. Additional slackwater deposit research is recommended on Katherine River (January 1998 flood), East Alligator River upstream of the area mapped in detail by Pickup et al (1983; 1987) and investigated by Murray et al (1992) and Wohl (1988; Wohl et al 1994a), and Magela Creek gorge below Magela Falls. The role of catastrophic floods in causing two avulsions on the East Alligator River floodplain at Cahill's Crossing also needs to be determined to assess the potential for avulsions on Magela Creek next to the rehabilitated mine site.

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Bryan Smith and Joan Mount are thanked for their considerable efforts in locating all of the publications that we requested at short notice. Ken Evans introduced us to the geomorphology and hydrology of ERA Ranger Mine and Kakadu National Park. Arthur Johnston, Bernard Prendergast and Ken Evans improved this report by sharing their knowledge of the Alligator Rivers Region and their expectations of this project. Robin Warner, Ellen Wohl and Steve Riley also assisted with the supply of information and/or discussion of the geomorphology of the Alligator Rivers Region. Their help is gratefully acknowledged. The Environmental Research Institute of the Supervising Scientist is thanked for sponsoring the visits to Jabiru, by Dr Wayne D Erskine and for commissioning this report. Selected additional information on the aerial inspections for this report is contained in Saynor and Erskine (1998). Ken Evans, Rob Warner, Ian Eliot and Peter Cornish constructively criticised and improved this report.

Assessment of the off-site geomorphic impacts of uranium mining on Magela Creek, Northern Territory, Australia

Wayne D Erskine and Michael J Saynor

1 Introduction

Energy Resources of Australia Ranger Mine (ERARM) is located in the 78 km^2 Ranger Project Area and is surrounded by the World Heritage listed Kakadu National Park (Johnston & Needham 1999) in the seasonally wet tropics of northern Australia (fig 1). Mining and production of uranium concentrate ar ERARM have been underway since 1981 (Johnston & Needham 1999). Mining of orebody No 1 was completed in 1994, the smaller orebody No 2 will not be mined, mining of orebody No 3 started in May 1997 (Johnston & Needham 1999) and should be completed by about 2007 (Johnston & Prendergast 1999). Tailings are currently stored in the above grade tailings dam and in the mined-out No 1 pit (Johnston & Needham 1999). At the completion of mining in about 2012, approximately 175 million tonnes of tailings, subeconomic grade ore and waste rock will require containment (East et al 1993, 1994). Artificial engineered landforms covering about 4 km^2 and up to 17 m above the surrounding area could be constructed (Willgoose & Riley 1993, 1998, East et al 1993, 1994, Riley 1995a, Evans et al 1998). Tailings containment structures, either above or below ground, are required to have an engineered structural life of 1000 years, over which time the tailings should be isolated from the environment (Fox et al 1977, East et al 1993, 1994). The mill tailings may be rehabilitated either in situ as part of the tailings dam (the above-grade option) or buried and capped in the mine pits (the below-grade option). Energy Resources of Australia has decided that all tailings will be returned to pits No 1 and 3 at a level no higher than mean sea level (Johnston & Needham 1999). The Commonwealth Government also approved the Ranger Mill Alternative for the neighbouring Jabiluka ore body in October 1997 subject to a braod range of requirements on environmental protection (Johnston & Prendergast 1999). However following refusal of the traditional land owners to permit the trucking of ore from Jabiluka to ERARM, the Jabiluka Mill Alternative was further developed and approved by the Commonwealth Government in August 1998 subject to a number of environmental requirements (Johnston & Prendergast 1999). Although mining at Jabiluka has been currently suspended, resumption will also generate waste materials.

Pickup et al (1983, 1987) were commissioned by the Supervising Scientist in 1982 to design a program of geomorphic research for the long-term management of uranium mill tailings. They recommended the following series of thirteen investigations to cover:

1. The erodibility of locally available construction materials, their susceptibility to erosion as determined by small plots, the development of an erosion computer model from the plot results, performance testing of the proposed final artificial landforms by both the computer model and field plots, and erodibility assessment of the natural slopes below the artificial landforms (Project R1).

2. The fluvial geomorphology of the Magela Creek system, in particular, the tributaries next to ERARM, the anastomosing sand-bed section upstream of Mudginberri, the Mudginberri Corridor and the lower Magela Plains (Project S1).
3. The potential transport, deposition and storage of mine tailings in the tributaries next to ERARM by developing a new mathematical model based on best current knowledge, local field data and sediment tracing (by studies of escaped mine tailings from the old Northern Hercules Mill at Moline) (Project D1).
4. The patterns of water and sediment movement on lower Magela Creek and its floodplain by remote sensing and dye tracing (Project D2).
5. Accurate estimates of the probability of rare catastrophic floods by slackwater deposits and palaeoflood analysis at the best sites in the Alligator Rivers Region, namely Katherine Gorge, East Alligator Gorge and upper Magela Creek Gorge (Project F1).
6. Detailed sediment budgets, hydrology and sediment sampling of small mine area creeks to determine their potential for containing escaped tailings and to develop a model of tailings dispersion (Project AD1).
7. Detailed assessment of historical channel changes on the four mine site tributaries, and on Magela Creek in the sand zone near the mine site based on all available vertical air photographs since 1950 (Project AD2).
8. The late Quaternary alluvial history of Magela Creek and the mine area tributaries upstream of Mudginberri, the identification of long-term sediment storages and the development and calibration of a mathematical model to simulate future behaviour (Project AD3).
9. The late Quaternary alluvial history of the Magela Creek backwater plain downstream of Mudginberri, the assessment of the impact of sea level changes on the plain, the determination of spatial variation in sedimentation rates, and further development and calibration of the mathematical model associated with Project AD3 (Project AD4).
10. Pollen dispersal on the Magela backwater plain to determine the vegetation communities and sedimentary environments represented by contemporary pollen rain (Project T1).
11. Long-term vegetation and climatic history over at least the last 6–7 ka, and possibly the last 18 ka, to provide analogues of a CO_2-warmed earth and the beginnings of the next glacial maximum (Project F2).
12. Holocene sea level change to determine both the response and rates of aggradation of the Magela backwater plain to sea level change (Project F3).
13. Oxidation and metal kinetics in Magela alluvium assuming a fall in sea level (Project AD6).

East (1985, 1986) reviewed this program and proposed a slightly modified list, which included most of the above as well as new projects on the role of termites on soil formation and erosion, as well as on the morphology and sedimentary characteristics of natural hillslopes. At least some progress has been achieved on all of these projects, as shown in table 1. Riley (1995a) consolidated the accumulated results to that time in a discussion of the main issues involved in an assessment of the long-term geomorphic stability of engineered landforms at ERARM.

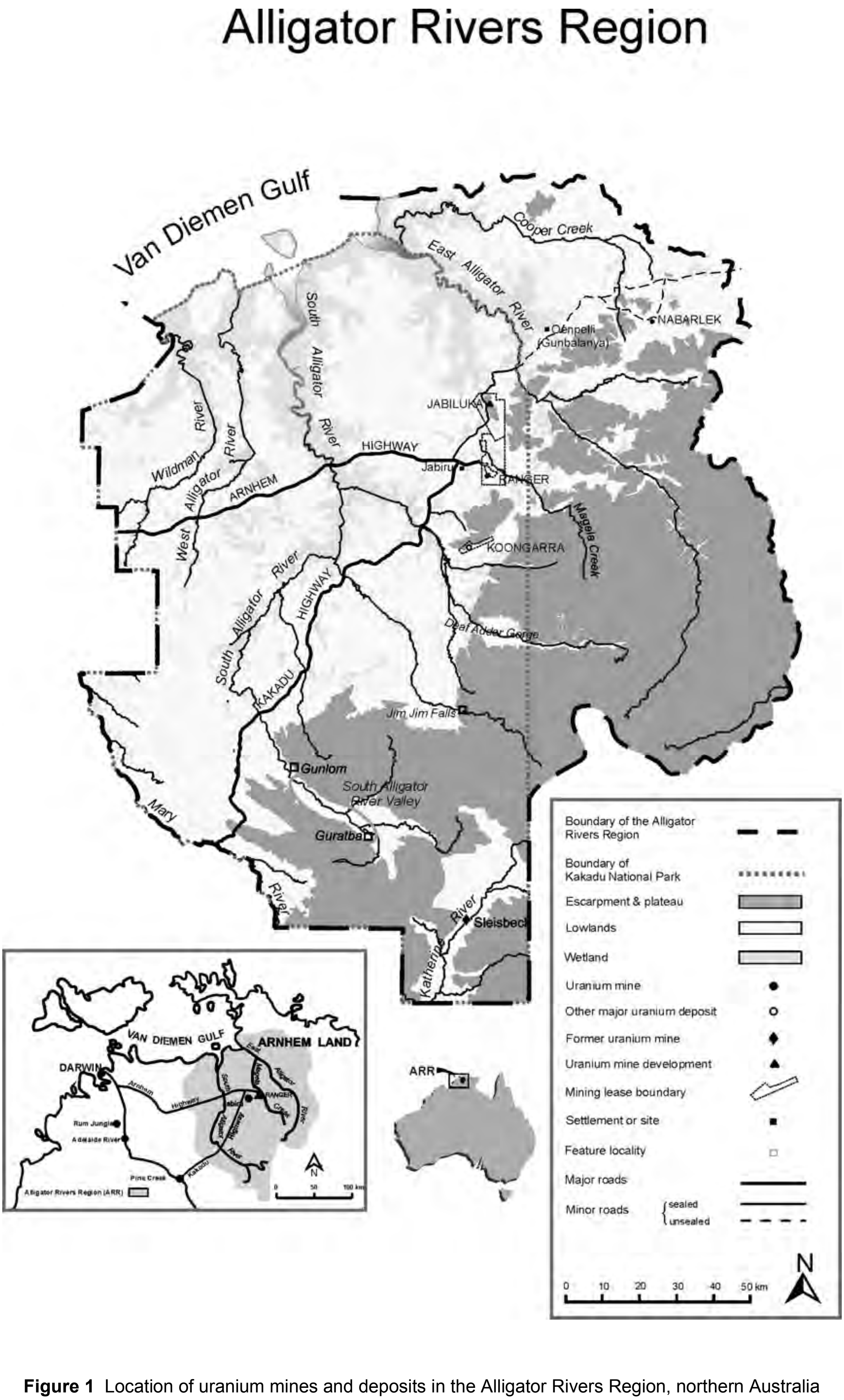

Figure 1 Location of uranium mines and deposits in the Alligator Rivers Region, northern Australia

Table 1 Completed geomorphic research on each project recommended by Pickup et al (1983, 1987)

Project Number	Project Title	Completed Work
R1	Erodibility of materials and alternative designs for ring dyke capping and embankment structures	Duggan (1985, 1988, 1994), East et al (1989a, 1994), Curley (1988), Uren (1990), Willgoose & Riley (1993, 1998), Riley (1992, 1994a, 1995b,d,e), Evans & Loch (1996), Unger et al (1996), Evans (1997), Evans et al (1998, 1999), Saynor & Evans (2000)
S1	Description and mapping of alluvial systems in the Alligator Rivers Region	Nanson et al (1990, 1993), Roberts (1991), Warner & Wasson (1992), East et al (1993)
D1	Potential transport, deposition and storage of tailings in small mine area tributaries	East et al (1988), Duggan (1985, 1988, 1994), Cull et al (1992), Riley & Waggitt (1992), Rippon & Riley (1996)
D2	Patterns of water and sediment movement in lower Magela Creek and its floodplain	Smith et al (1985), Murray et al (1993)
F1	Frequency analysis of floods using slackwater deposits	Baker et al (1985, 1987), Baker & Pickup (1987), Murray et al (1992), Wohl (1988), Wohl et al (1994a)
AD1	Sediment budget of small mine area creeks	Duggan (1985, 1988, 1994), Cull et al (1992)
AD2	Medium term system behaviour	Nanson et al (1990, 1993), Roberts (1991)
AD3	Evolution of Magela Creek channels, floodplains and mine area tributaries upstream of Mudginberri	Nanson et al (1990, 1993), Roberts (1991), East et al (1993)
AD4	Evolution of Magela Creek backwater plain downstream of Mudginberri	East et al (1989b), Clark et al (1992a,b), East et al (1992)
T1	Pollen dispersal on the Magela backwater plain	Clark & Guppy (1988), Clark et al (1992a)
F2	Long term vegetation and climatic history	Clark & Guppy (1988), Clark et al (1992b)
F3	Holocene sea level change	Woodroffe et al (1986, 1987, 1989), Clark et al (1992b)
AD6	Oxidation and metal kinetics in Magela alluvium	East et al (1992), Willett (1992)

Extensive research has been conducted on the hydrology, erosional processes and landform evolution of the ERARM waste rock dumps over the last 15 years (for examples, see Willgoose & Riley 1993, 1998, East et al 1994, Riley 1994a, 1995a,b, Evans & Loch 1996, Unger et al 1996, Evans 1997, Evans et al 1998, 1999, Saynor & Evans 2000). The results of this work are being used to assess the adequacy of proposed structures and rehabilitated landforms in relation to their stability. SIBERIA, a landform evolution model, has been used for this purpose (Willgoose & Riley 1993, 1994, 1998, Unger et al 1996, Evans 1997, Evans et al 1998). The design selected should, among other things, minimise both short- and long-term, off-site impacts. Assessment of off-site impacts requires detailed information on exported solute and particulate loads as well as on the fate of this material once it leaves the mine site (Riley & Waggitt 1992). Previous work has been completed on these topics and needs to be reviewed to establish whether it is adequate for off-site impact assessment. The purpose of this report is threefold:

1. To collate and review all of the existing data relevant to the discharge of solutes and particulate material from the rehabilitated mine site and from nearby tributaries of Magela Creek;
2. To determine the fate of particulates in the off-site system; and
3. To collate and review all of the existing material relevant to an understanding of the long-term behaviour of Magela Creek and its tributaries.

A brief introduction to the regional geomorphology of the Alligator Rivers Region is presented first to provide a spatial framework for the following work. The dynamics of soil and solute losses from the waste rock dump on ERARM and other disturbed areas as well as from undisturbed areas in the Alligator Rivers Region are then discussed before reviewing the particulate and solute yields reported for the same area. Then the likely fate of particulates discharged from the mine site is assessed from the published work and the need for additional work on the magnitude and frequency of extreme flood events and their impact on the landscape, is outlined. The long-term behaviour of Magela Creek and its tributaries is presented next before drawing the main conclusions and recommendations from the above review.

2 Regional geomorphology

Jennings and Mabbutt (1986) mapped two geomorphic regions in the Alligator Rivers Region, which they called the Bonaparte-Diemen Lowlands and the West Arnhem Plateau. The former are dissected lateritic lowlands also containing alluvial, estuarine and coastal plains whereas the latter is a dissected sandstone plateau. These formally defined regions are too broad for present purposes and so they are further subdivided below. The geomorphology of the Alligator Rivers Region has been outlined by Williams (1969a, 1991), Galloway (1976), Russell-Smith et al (1995) and East (1996), among others. They have described the main landforms relevant to this report as the Arnhem Land plateau, the Arnhem escarpment, the Koolpinyah erosion surface, the alluvial plains and the deltaic estuarine floodplains. The first two are part of the West Arnhem Plateau whereas the last three are part of the Bonaparte-Diemen Lowlands. Each of the above landforms is briefly described below.

The Arnhem Land plateau is an exhumed, essentially bedrock, tabular upland (fig 2), which constitutes the upper catchment of most major rivers. It is formed predominantly of resistant, horizontally-bedded, vertically jointed, quartz sandstone of the Middle Proterozoic Kombolgie Formation and produces low sediment yields of predominantly sandy material (Roberts 1991). A deeply incised, trellised drainage pattern has developed along the closely spaced joints and faults. Williams (1991) emphasised that the sandstones have long operated as a very effective caprock, protecting the underlying rocks from erosion. Outliers of sandstone form isolated massifs, such as Mt Brockman and Nourlangie Rock, at varying distances from the main plateau.

The Arnhem escarpment is the most striking scenic feature of Kakadu National Park and marks the edge of the plateau (fig 3). It varies from about 30 to 330 m high and exhibits a range of different forms depending on the underlying geologic structure (Galloway 1976). Quartz sandstone of the Kombolgie Formation outcrops in the scarp, which retreats episodically by collapses of large sandstone blocks, followed by centuries of near stability. Galloway (1976) speculated that the rate of scarp retreat may be of the order of 1 m/1000 years but Roberts (1991) calculated rates of only 0.02–0.2 m/1000 years. Rivers leaving the plateau either flow over the scarp as spectacular waterfalls (fig 4) or dissect the scarp by relatively long, narrow, deep bedrock gorges that follow joints and faults (fig 5). Near the escarpment, Roberts (1991) found that sand fans began to accumulate at 230–220 and 120–100 ka, which coincide with the start of the penultimate and last interglacials, respectively. Roberts et al (1990) reported the then oldest dates of human occupation in Australia (50–60 ka) based on thermoluminescence dating of these sandy footslope deposits, which contained Aboriginal artifacts.

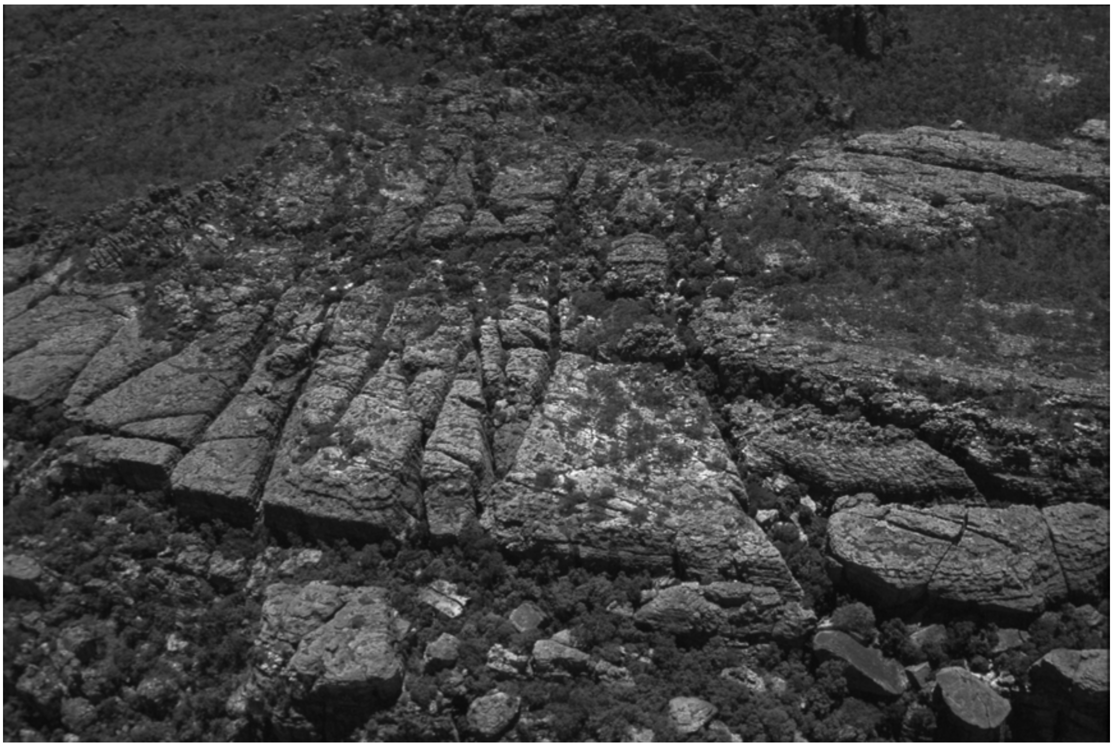

Figure 2 The Arnhem Land plateau showing the tabular landscape dissected along closely spaced joints (Saynor & Erskine 1998)

Figure 3 The Arnhem escarpment at the head of Magela Creek showing the horizontally bedded quartz sandstone of the Kombolgie Formation exposed in the cliff line

Figure 4 Magela Falls in February 1998 (Saynor & Erskine 1998). The falls retreat by basal undercutting followed by blockfall, producing a straight bedrock gorge that follows the regional joint pattern. The gorge is a suitable site for slackwater deposition and palaeoflood analysis (Pickup et al 1983, 1987), as outlined in section 6.

Figure 5 The straight bedrock gorge of the East Alligator River that deeply dissects the Arnhem Land plateau (Saynor & Erskine 1998). This gorge is also a suitable site for slackwater deposition and palaeoflood analysis (Saynor & Erskine 1998) but is located upstream of the area mapped by Pickup et al (1987).

The extensive undulating lowlands between the Arnhem Land escarpment and plateau, and the floodplains of the major rivers in the Alligator Rivers Region have been called the 'Koolpinyah Surface' (Hays 1967). It was originally believed to be a Tertiary lateritised palaeoplain (Hays 1967, Williams 1969a, 1991, East et al 1993). Thorium-uranium disequilibrium dating of iron pisoliths from the same shallow soil horizon below the Koolpinyah Surface yielded ages of 135 to 202 ka, with a mean of 176 ka (Short et al 1989). Short et al (1989) interpreted this result to mean that there was a second phase of lateritisation of the Koolpinyah Surface in the late Quaternary following the earlier main Tertiary phase. More recent work by Nanson et al (1993) found thorium-uranium dates of >400 ka on iron pisoliths in a river terrace on Magela Creek inset into the Koolpinyah Surface. Isotope ratios in one sample show that the pisolith was probably older than 1.3 Ma. Therefore, the Koolpinyah Surface must be older than the river terrace. Nanson et al (1993) also demonstrated that ferruginisation was probably an ongoing process under contemporary climatic conditions. However, Nott (1995) concluded that the Koolpinyah Surface is an exhumed Proterozoic surface extending below the Arnhem Land plateau. Williams (1969b) rightly concluded that this surface had a complex and polygenetic history. Chartres et al (1991) investigated in detail the soils formed on a small area of the Koolpinyah Surface near ERARM. They found that the soils were generally shallow and gravelly, and overlie weathered, ferruginised schist of the Cahill Formation at relatively shallow depths. Clay and organic matter contents were low, cation exchange capacity was extremely low and the clays were low activity clay minerals, with kaolinite dominating. This was consistent with Williams's (1969a) findings that, near the East Alligator River, very little of the original Koolpinyah Surface remains because it has been extensively eroded. Nevertheless, the Koolpinyah Surface is an extremely old landscape and appears to be very stable (Galloway 1976, East et al 1993, East 1996). East et al (1993) recommended that rehabilitated mine structures associated with ERARM should be sited on this surface, as indeed they have been (fig 6).

Figure 6 ERARM located on the stable, lateritised Koolpinyah erosion surface beside Magela Creek and below the Mt Brockman outlier (Saynor & Erskine 1998)

Rivers crossing the Koolpinyah Surface have cut shallow trenches, which are occupied by sandy river channels, wetlands, floodplains, river terraces and palaeochannels (Galloway 1976, Pickup et al 1987, Nanson et al 1990, 1993). This suite of landforms is called the 'alluvial plains' (fig 7). Multiple Pleistocene terraces and palaeochannels of clayey, silty and sandy sediments flank the contemporary sandy anastomosing channels below the Arnhem escarpment (Nanson et al 1990, 1993). Many are currently flooded during the Wet season. The present channel of Magela Creek started aggrading with sand about 5–7 ka and largely infilled the trench excavated during the low sea level of the last glacial maximum. This sand is progressively prograding downstream and is slowly burying flood basins, billabongs and wetlands. Extensive flood basins of Holocene organic clay sediments lie between the upstream sandy alluvial plain and the downstream deltaic estuarine plain. The flood basin sediments often stratigraphically overlie estuarine sediments (Woodroffe et al 1986, 1989, Clark et al 1992a,b).

Figure 7 Alluvial plain of Magela Creek upstream of Mudginberri showing contemporary sand-bed anastomosing channels (separated by sand islands), river terraces and Pleistocene palaeochannels, ie the grassed depressions on the right of photograph (Saynor & Erskine 1998)

Extensive 'deltaic estuarine floodplains' (fig 8) are present on the lower South Alligator, West Alligator and East Alligator Rivers. These estuaries exhibit four distinct channel types, which, in upstream sequence are the estuarine funnel, sinuous reach, cuspate reach and the upstream reach (Woodroffe et al 1986, 1989). Each channel type is also associated with a distinctive stratigraphy (Woodroffe et al 1986, 1989). The deltaic estuarine plain developed in three major phases over the last 8 ka as sea level rose from about -14 m AHD to its present level after 5.8 ka BP (Woodroffe et al 1986, 1987, 1989). The 'transgressive phase' (8–6.8 ka BP) marked the final marine flooding of the prior valley and the development of mangrove forests. Then the 'big swamp phase' (6.8–5.3 ka BP) occurred as sea level stabilised around its present level and mangrove forests became established over most of the present floodplain. The 'sinuous/cuspate phase' began about 5.3 ka BP and was characterised by the establishment of a meandering estuarine channel flanked by a marginal zone of mangroves. Freshwater swamps developed and overbank deposits were laid down on the floodplain surface over the last 4–1.5 ka BP. The Holocene depositional history of the deltaic estuarine plain on Magela Creek is discussed in detail in section 7. Although there is a coastal plain fronting van Diemen Gulf (East 1996, Bayliss et al 1997), it is not relevant to the present discussion.

Figure 8 The deltaic estuarine plain of Magela Creek and the East Alligator River during the 1997/1998 Wet season, showing the point bar of the cuspate meandering segment of Woodroffe et al (1989) on the East Alligator River at the top of the photograph (Saynor & Erskine 1998)

3 Soil and solute losses from the waste rock dump, other mined areas and natural slopes

The results of soil loss rates measured on mine sites and natural hillslopes of the Koolpinyah Surface in the Alligator Rivers Region and neighbouring areas under 'natural' rainfall are summarised in table 2. Some of this work precedes the recommendations of Pickup et al (1983, 1987). Williams' (1973) pioneering work revealed that on undisturbed tropical granite slopes, the volume of soil moved downslope each year by soil creep was on average 5.0 times less than that moved by slopewash. On sandstone slopes, the difference was 5.2 times (table 2). While these differences are significant, there were no significant differences between the rates of both processes for the two lithologies. These results demonstrate that natural rates of soil erosion in the seasonally wet tropics of Australia are very low by world standards (Saunders & Young 1983) and justify the concentration on slopewash processes by experimental work at ERARM (see below).

Williams (1976, fig 22) found from short-term measurements on a single plot in the Alligator Rivers area that soil loss was linearly related to total storm rainfall. Furthermore, data for two plots showed that soil loss also increased linearly with total raindrop momentum but was over 20–30 times greater at the onset of the Wet season for the same unit rainfall momentum than during the middle of the Wet season. These differences were related to a much lower ground cover at the start of the Wet season. Rainfall intensity increased as the Wet season progressed and mid- to late-Wet season rainfall therefore had higher momentum. Williams (1976) concluded that the effect of the increased grass protection exceeded that of the increase in erosive potential due to rainfall intensity. Painted stones on the surface of sandstone slopes moved at mean rates of up to 40 mm/yr and at maximum rates of 100–400 mm/yr (Williams 1974, 1976). The percentage of stones moving at any site increased linearly with the sine of the slope angle (Williams 1974, 1976).

Duggan (1988, 1994, but see 1985 also) used 51 transects (arranged along the contour), each of 100 erosion pins, between 1979 and 1983 to measure soil loss rates under natural rainfall in the Alligator Rivers Region (table 2). These consisted of 20 transects in undisturbed areas, 7 transects in undisturbed areas that had been burnt during the previous Dry season and 24 transects in mine leases that had been disturbed and subsequently rehabilitated. Deposition dominated on 19 of the 20 unburnt, natural transects and on 5 of the 7 burnt but natural transects. As a result, a net increase (deposition) in ground surface level was recorded, as denoted by the negative sign in table 2 (ie by convention, all changes below the original ground surface are denoted as positive or ground surface lowering and all changes above, as negative). The three transects with net erosion had minor to no gravel lag protecting the soil surface. Erosion dominated on 19 of the 24 cleared and rehabilitated transects, yielding a net lowering of 1.25 mm/yr. Duggan (1988, 157) concluded that 'sediment eroded from upslope is transported as a pulse resulting in downslope deposition'.

Table 2 Results of particulate yields for soil erosion experiments in the Alligator Rivers Region and nearby areas of the Northern Territory

Author	Site	Method	Sample size	Sediment yield ($t/km^2.yr$)[a] or ($cm^3/cm.yr$)[b]	Denudation rate (mm/yr)
Williams (1973, 1976)	Brocks Creek: Granite	Young (1960) soil creep pits	15	7.33[b]	0.018
	Brocks Creek: Granite	Young (1960) slopewash trays	13	36.34[b]	0.054
	Mary River: Sandstone	Young (1960) soil creep pits	12	4.39[b]	0.011
	Mary River: Sandstone	Young (1960) slopewash trays	9	22.86[b]	0.056
Curley (1988)	Ranger waste rock dump	Bounded plots with flumes	3	29.7[a]	0.04
Uren (1990)	Ranger waste rock dump	Erosion pins	308[1] 308[2] 379[3] 385[4]	– – – –	-1.85* -2.00* -1.18* -1.60*
Cull et al (1992)	Jabiluka, Nabarlek and Ranger	Rate of advance of weathering front	45	25[a]	0.04
Riley (1994b, 1995c)	ERARM waste rock dump	Bedload erosion plots	Not specified	400[a]	2-3
Duggan (1985, 1988, 1994),	Nabarlek[V]	2 m^2 plot	3	2317[a]	3.2
	Nabarlek[R]	2 m^2 plot	1	1000[a]	1.4
	Nabarlek[N]	2 m^2 plot	1	5100[a]	7.0
	Kakadu	Erosion pins	2000	–	-1.25*
	Kakadu	Erosion pins	700	–	-0.33*
	Kakadu	Erosion pins	2400	–	1.25

[1] Plot 1
[2] Plot 2
[3] Plot 3
[4] Plot 4
V revegetated
R rock mulch or surface veneer
N no stabilisation techniques
* negative sign denotes deposition

Curley (1988) also used rows of erosion pins on straight and concave slopes on the waste rock dump during the 1987/88 Wet season and found evidence of deposition on the lowest row of pins. However, his results are not discussed here because he concluded from substantial discrepancies between erosion pin rates and measured sediment yields on the same plots that 'clearly most of the pin measurements can be ascribed to settlement over the surface of each slope' (Curley 1988, 38).

However, during the next Wet season, deposition or no change was recorded on every row of every plot (Uren 1990). As a result, the trend of the means indicated that deposition had occurred on every bounded plot (table 2), despite sediment being transported off the plot (Uren 1990).

More recent work in south-eastern Australia (Saynor et al 1994), has found similar trends. The sediment pulses were called slugs, following the terminology of Erskine (1993, 1994a) for large, sand-aggraded bedforms in rivers. It must be emphasised that Duggan's (1988, 1994) and Uren's (1990) results are impossible in the long-term because they imply that particulates are being created (Saynor et al 1994). Nevertheless, similar results have also been obtained following logging in the forests of south-eastern Australia (Mackay et al 1985). However, Saynor et al (1994) found that net deposition is often recorded when grids or contour-aligned transects are used. Furthermore, micro-basins or closed circular depressions about 1 m in diameter and about 0.07 m deep have been described on quartzite ridges in Arnhem Land and are known to trap sediment transported by shallow overland flows (Riley et al 1997). Pins must only be used on complete slope transects from the top to the bottom of the slope following the path of maximum slope to determine the rate of ground surface lowering (Saynor et al 1994). Otherwise, only local sediment redistribution is measured and predictions of ground surface lowering cannot be made.

Despite the problems with Duggan's (1988, 1994) erosion pin results, they do indicate that natural erosion rates are very low to immeasurable. Such an interpretation is consistent with Williams's (1973) results. Only when disturbance has occurred is erosion active enough to be measured by the pin technique. Duggan's (1988, 1994) plot results on steep (17°) embankments at the Nabarlek mine site showed very high erosion rates, even when various protective measures had been used. Rock mulching was more effective than revegetation in reducing soil losses in this strongly seasonal climate.

Riley (1992, 1995b) used the small portable flume of Riley and Gore (1988) to determine that slopes on the waste rock dump were 10 to 100 times more erodible than adjacent natural slopes. Furthermore, sediment concentrations decreased exponentially over time when runs persisted for more than 5 minutes by the preferential erosion of finer sediment from the ground surface. Clay was enriched in the runoff in comparison to the source soils but sediment exhaustion still occurred. Riley and Gardiner (1991) used a rainfall simulator to apply a range of storms in order of increasing magnitude up to >1:100 years on two plots on the waste rock dump. They again found sediment exhaustion during and between runs, a strong linear relation between stream power and sediment discharge, and that finer sediment was preferentially eroded. However, they also recorded an inverse relation between sediment concentration and stream power, which they did not explain.

Duggan (1988, 215) noted that 'The lack of quantified association between surface lowering, slope, soil type and vegetation cover prevents prediction using methods such as the Universal Soil Loss Equation.'

This was interpreted to indicate that a new erosion model, based on, or calibrated to, local conditions, must be used. Riley (1992, 1995b) also found that there was a lack of significant relations between hydraulic parameters and sediment discharge for his small flume runs, indicating the difficulty in developing predictive erosion models. However, Riley and Gardiner (1991) found ‘strong’ relationships between sediment concentration and both sediment discharge, and stream power for their rainfall simulator runs but there was an unexplained and unexpected ‘inverse’ relation between sediment concentration and stream power. This indicates pronounced sediment exhaustion between successive runs and the inappropriateness of conducting successive runs on the same plot.

However, Riley (1994b, 1995c) used a version of the Universal Soil Loss Equation to assess the stability of the Nabarlek tailings pit cover but did not outline how the parameter values were determined. Evans and Loch (1996) used the Revised Universal Soil Loss Equation to explain the measured differences in erosion rates between the cap and batters of the waste rock dump at ERARM (see below). They carefully derived parameter values from detailed field and laboratory work. Nevertheless, the computer erosion model SIBERIA (Willgoose et al 1991, Willgoose 1992), calibrated to site conditions, has been employed to assess the long-term erosional stability of the proposed artificial rehabilitated landforms at ERARM (Willgoose & Riley 1993, 1994, 1998, Evans 1997). SIBERIA is further discussed below.

Gullies up to 1 m deep have formed during one Wet season on disturbed slopes of less than 2° but are rare on undisturbed, natural slopes of the Koolpinyah Surface in the Kakadu region (Duggan 1988). Vehicle tracks, former cattle and buffalo tracks, buffalo wallows, pads, pugged ground and damaged vegetation have been important in destroying protective gravel lags and removing ground cover, thus initiating gullies (Williams 1976, Duggan 1988, Skeat et al 1996). Williams’s (1976) sediment yield for a single gully at Jabiru (table 4) and the quantification of soil loss from one gully on Fisher Creek by Skeat et al (1996) serve to highlight the magnitude of the problem when gullies are actively developing. However, gully erosion rates exponentially decline over time following initiation (Graf 1977).

A feature of Duggan’s (1985, 1988, 1994) work has been an attempt to apply her soil erosion results to the development of innovative, locally oriented, soil conservation practices suitable for mine rehabilitation. She quite rightly concluded that vegetation was not important in reducing soil erosion at the beginning of the Wet season when 60% of the total annual erosion on disturbed bare surfaces occurs and that a number of other factors contributed to the low natural erosion rates. Significant litter cover and the formation of litter dams created a stepped microtopography conducive to substantial sediment storage on slopes (Mitchell & Humphreys 1987, Evans et al 1999). Litter or debris dams have been observed after rainfall simulation experiments on the ERARM waste rock dump (Evans et al 1999). Of greater importance was the widespread development of gravel surface lags that provide mechanical resistance to raindrop splash and shallow overland flows. Their reinstatement by methods similar to the standard stripping, stockpiling and subsequent replacement of topsoil following mining was recommended. This practice should be adopted at all mine sites in the Alligator Rivers Region.

Riley (1995e) used a small rainfall simulator (plots of 1 m^2) on bare areas of the waste rock dump to determine the effects of vegetation on rainsplash erosion. He used permeable shade cloth to simulate low vegetation. Rainsplash erosion on bare surfaces was reduced by a factor of 4 to 10 by the simulated vegetation cover. Riley (1995d) summarised the results of field measurements of the amount of rainsplash under different vegetation covers for 22 storms. The amount of rainsplash under trees and on bare areas was approximately equal and was about double that under grasses and shrubs. Clearly low ground cover significantly reduced rainsplash and should be used, where possible, in mine rehabilitation.

Saynor and Evans (2000) determined the effect of vegetative growth during the 1994/95 Wet season on runoff and soil loss rates from plots on the ERARM waste rock dump. They found that the greatest runoff and soil loss rates occurred from the unvegetated cap site and that the lowest runoff and soil loss rates occurred from the densely vegetated fire site. Furthermore, as vegetation density increased, the percentage of suspended sediment decreased. Soil loss rates from the vegetated plots during the Wet season decreased at a decreasing rate until reaching an essentially constant rate midway through January.

Cull et al (1992) used the behaviour of weathering zones in the metamorphic rocks that host uranium mineralisation at Nabarlek, Ranger and Jabiluka to determine medium term denudation rates. The mean of all the estimated denudation rates is listed in table 2. This mean is representative of the denudation rate over the last 59 ± 6.7 ka and indicates the rate of lowering of the Koolpinyah Surface. This rate has a high standard deviation.

East et al (1989a, 1994) summarised the early research on soil and solute losses from the waste rock dump and nearby natural hillslopes that had appeared in a number of conference papers and Annual Research Summaries of the Alligator Rivers Region Research Institute. They found that stable natural hillslopes exhibited convexo-concave profiles with protective lags or surface veneers of resistant gravels, which protect the soil surface against erosion, on the steeper segments. Basal slope segments were characterised by long flat concavities with relatively fine-grained surficial sediments and the steeper upper slope segments, by short convexities with extensive, very to extremely poorly sorted, gravel lags. They used four erosion plots on batter slopes of the waste rock dump at ERARM to quantify the combined effects of slope profile shape and surface rock cover on soil losses. Two plots were 56 m long and 22 m wide with straight slopes and two were 78 m long and 22 m wide with a concave profile. For each slope profile, one plot was surfaced with run-of-quarry waste rock and one with more resistant chlorite schist. Revegetation was not attempted. No sediment or solute yields were reported for these plots and hence they cannot be included in table 2. Plot results for individual Wet seasons were reported in the theses by Curley (1988) and Uren (1990). East et al (1989a, 1994) found that the concave plots, despite being longer, always produced smaller peak discharges of shorter duration with lower runoff coefficients and higher infiltration rates. Suspended solids concentrations varied directly with discharge and were always higher for straight slopes than for concave slopes. There was no exhaustion of suspended solids concentrations for the same discharge during the Wet season. Vegetation would obviously change these results. Significant quantities of bedload were trapped in troughs only on the straight slopes. Solute concentrations, as expected (Gregory & Walling 1973), always varied inversely with discharge. However, mean solute concentrations were always higher for the chlorite schist cover than for the run-of-mine waste rock. Late Wet season solute concentrations were about an order of magnitude lower than those for the early Wet season, indicating solute exhaustion. They also outlined the physico-chemical properties of the waste rock and the variations in the major ions with discharge for the plots. They recommended that the design of rehabilitated mine structures should incorporate features of natural stable landforms (ie convexo-concave profiles and surficial gravel veneers) because of their superior erosional stability over conventionally engineered landforms. These practices should be adopted at all mine sites in the Alligator Rivers Region.

Evans (1997) reported the results of monitored natural rainfall events for four plots on the waste rock dump at ERARM. These plots were called:

- *cap site* (plot area of 591 m^2 with an average slope of 2.8% and with a surface cover of fine material over a pan);

- *batter site* (plot area of 600 m^2 with an average slope of 20.7% and with an armour of coarse material);
- *soil site* (plot area of 600 m^2 with an average slope of 1.2% and with a topsoiled, ripped and vegetated surface); and
- *fire site* (plot area of 600 m^2 with an average slope of 2.3% and with a top-soiled, ripped and vegetated surface containing established trees).

The data for these plots is contained in Evans and Riley (1993a,b) and Saynor et al (1995), and has been summarised and analysed by Evans (1997, Evans et al 1998). Complete data sets of rainfall, runoff and sediment load were obtained for 5 events on the cap site, 4 events on the batter site, 10 events on the soil site and 9 events on the fire site. Total rainfall for these monitored events ranged from 6 to 50 mm and maximum 10 minute rainfall intensities ranged from 24 to 132 mm/h. The mean runoff coefficients with standard deviations for these events were 0.77 ± 0.18 for the cap site, 0.41 ± 0.13 for the batter site, 0.10 ± 0.03 for the soil site and 0.04 ± 0.02 for the fire site. The very low runoff for the fire site was partly caused by the loss of runoff into a crack that did not discharge into the outlet trough. One event on the cap site produced a runoff coefficient of 1.06 which is impossible unless runoff was still occurring from an earlier event or unless there was a measurement error. Runoff and sediment loss per unit runoff from the cap and batter sites were much greater than from the soil and fire sites for events with similar total rainfall and intensity. Clearly, vegetation and surface ripping reduce runoff and erosion. An unusual result of the above monitoring was that bedload yields *always* exceeded the suspended load yields on all plots, which is also consistent with the results of Saynor and Evans (2000).

Evans (1997) also found that high intensity storms eroded disproportionately high soil losses from the plots. For example, the largest event on the cap and batter sites removed 69% and 73%, respectively of the total soil loss. The two largest events on the soil site removed 54% of the total soil loss. For the high intensity storms on the cap and batter sites, total soil loss per unit runoff increased by an order of magnitude compared to the lower intensity storms (Evans 1997). Clearly high intensity storms are important agents of soil erosion in the Alligator Rivers Region.

The data in table 2 indicate that the *maximum* soil loss expected from the 4 km^2 of rehabilitated landforms at ERARM over the 1000 years structural life is 20.4 x 10^6 t. This estimate was derived using Duggan's (1988, 1994) results for a single 2 m^2 plot at Nabarlek that was disturbed but had no soil stabilisation techniques implemented. It assumes that the climatic and soil conditions are similar between the Nabarlek and Ranger mine sites. This soil loss equates to a maximum depth of erosion of 7 m, assuming that erosion is uniformly distributed over the whole 4 km^2 area. This, of course, will not be the case because areas of concentrated flow will erode faster. Erosion rates usually decline exponentially over time following disturbance, eventually returning to background levels (Duggan 1988). Furthermore, erosion rates are greater for smaller than for larger areas (Cull et al 1992, Erskine & Saynor 1996a). Therefore, such erosion represents a worst possible case scenario for ERARM. However, the uncertainty associated with the extrapolation of the results for a single erosion plot is very large. Nevertheless, the prediction agrees closely with those of the SIBERIA catchment evolution model. Evans (1997, Evans et al 1998) found that SIBERIA predicted a maximum erosion depth of 7.6 m over 1000 years on the rehabilitated mine site. Willgoose and Riley (1998) predicted peak erosion depths of 7 to 8 m *without gully development and with no vegetation cover* on the structure over the same time. The cap of the rehabilitated mine site away from flow paths would exhibit <0.5 m of erosion while the steep batter slopes would exhibit 5–7 m of erosion. Up to 5 m of deposition was predicted very close to the batters. The earlier modelling of Willgoose and Riley (1993) predicted a maximum erosion depth of 7.7 m, maximum deposition of 6.1 m and batter erosion of 3–7 m *without gully development and with no vegetation cover*. Depths of erosion at 500 years were 74–75% of those at 1000 years (Willgoose & Riley 1993, 1998). Though these values are similar, a factor of safety should be adopted for design purposes (Riley 1994b, 1995b). Willgoose (1995) repeated the SIBERIA simulations of Willgoose and Riley (1993) over 1000 years with fully developed vegetation (undergrowth and canopy) and predicted the erosion to be only 5.8% of the unvegetated erosion. The reduction would range between 5.8 and 75% if the undergrowth was not fully developed. For a vegetated and ripped condition, Evans et al (1998) found that SIBERIA predicted a maximum erosion depth of only 2.2 m.

4 Particulate and solute yields from disturbed and natural catchments

The annual inputs of nutrients in precipitation to the Magela and Nourlangie Creek systems were determined by Noller et al (1985) and are shown in table 3. These amounts are low but similar to those reported from other northern Australia sites (Noller et al 1985). Rainfall is acidic and has a low dissolved solids content (Noller et al 1990, Gillett et al 1990).

Table 3 Annual inputs of selected nutrients in precipitation (kg/ha.yr) to Magela and Nourlangie Creek systems during the 1982/83 Wet season (Noller et al 1985)

River	Ca^{2+}	Mg^{2+}	K^+	Na^+	PO_4^+	Cl^-
Magela Creek	0.44 ± 0.09	0.40 ± 0.11	1.1 ± 0.5	3.0 ± 0.5	0.4 ± 0.2	10 ± 1.9
Nourlangie Creek	0.47 ± 0.01	0.42 ± 0.03	0.96 ± 0.2	3.8 ± 0.9	0.3 ± 0.1	13 ± 5.1

The available particulate and solute yields for disturbed and natural catchments in the Alligator Rivers Region and nearby areas of the Northern Territory are collated in table 4. Cull et al (1992), Riley (1994b, 1995c), Skeat et al (1996) and East (1996) have also compiled similar data for natural catchments but all their data sets are incomplete. Cull et al's (1992) and Riley's (1994b, 1995c) citations of Williams's (1976) and Woodroffe et al's (1986) results are incorrect, as is the citation of Duggan's (1988) results for Koongarra Creek by East (1996) and Skeat et al (1996). Nanson et al (1993) summarised the reported sediment yields but failed to include any for disturbed catchments. Beardsell et al (1989) and Lancaster (1990) only measured in detail the suspended sediment load at one station on the South Alligator River (El Sharana, 1238 km^2) and estimated the yields at the other three sites from occasionally measured suspended sediment concentrations. Total sediment load yields refer to the combined wash load and bedload of Einstein et al (1940). Total terrigenous yield refers to the combined suspended load and solute yields. It must be emphasised that the yields in table 4 have been calculated by different methods and for different time periods by different researchers. As a result, they may not be strictly comparable. Duggan's (1988, 1994) yields are based on the most data and are, therefore, considered the most reliable, despite using rating curves to estimate loads, which are known to be inaccurate (Rieger & Olive 1988). Nevertheless, a synthesis of available information, as attempted here, can only use the original results.

Table 4 Results of particulate and solute yields for the Alligator Rivers Region and nearby areas of the Northern Territory

Author	Time period	Site	Yield ($t\ km^{-2}yr^{-1}$)
Williams (1976)	1973	Jabiru gully – 0.0008 km^2	93 750[1]
	1964–68	Adelaide River – 660 km^2	11.2[2]
Fox et al (1977)	Unspecified	Jabiru – Magela Creek	7.5[2]
Hart et al (1982)	1978–79	Gauge 8210009 – Magela Creek – 600 km^2	4.9[2]
Hart et al (1986)	1982–83	Gauge 8210009 – Magela Creek – 600 km^2	3.7[2]
Hart et al (1987b)	1982–83	Gauge 8210009 – Magela Creek – 600 km^2	3.9[2]
			2.1[3]
	1982–83	Gauge 821019 – Magela Creek – 1570 km^2	1.1[2]
Woodroffe et al (1986)	Last 2000 yrs	South Alligator River – 9000 km^2	22.2
Curley (1988)	1987–88	Ranger waste rock dump – 0.00106 km^2	29.7[2]
Duggan (1985, 1988, 1994, unpublished)	1981–83	Gauge 820400 – Koongarra Creek[N] – 5.4 km^2	30.1[2]
			10.1[3C]
			40.2[4]
	1981–83	Gauge 821400 – 7J Creek[N] – 3.5 km^2	9.4[2]
			5.1[3C]
			14.5[4]
	1984–87	Gauge 821402 – Gulungul Creek[N] – 61.9 km^2	34.8[2]
			5.9[3C]
			40.7[4]
	1984–85	Georgetown Creek[N] – 7.8 km^2	32.1[2]
			14.0[3C]
			46.1[4]
	1985–87	Gauge 821401 – Georgetown Creek 2[N] – 4.8 km^2	6.3[2]
			2.6[3C]
			8.9[4]
	Unspecified-1 year	Kawudjulah Creek – 63 km^2	19.0[2]
	1979–83		
		Ranger Tributary[D] – 0.22 km^2	2460[2a]
	1979–81		890[2b]
	1979–82	Ranger Tributary[D] – 0.47 km^2	833[5]
		Nabarlek Tributary 1[D] – 0.78 km^2	2420[2a]
	1981–83		1083[2b]
		Jabiru Tributary 1[D] – 0.15 km^2	2182[2a]
	1982–83		1101[2b]
		Jabiru Tributary 2[D] – 0.029 km^2	188[2]
Cull et al (1992)	1978–83	Gauge 8210009 – Magela Creek – 600 km^2	9.15[2]
	1979–81	Gauge 821017 – Magela Creek – 1115 km^2	3.35[2]
	1978–80 1982–83	Gauge 821019 – Magela Creek – 1570 km^2	2.30[2]
Roberts (1991)	1971–89	Gauge 8210009 – Magela Creek – 600 km^2	17.5[1]
			11.8[2]
			2.5[3C]
			20.0[4]
			8.5[5]
			9.0[6]
Beardsell et al (1989)	1988–89	Koolpin Creek – 477 km^2	#13.5[2]
Lancaster (1990)	1988–89	Fisher Creek – 324 km^2	#149.5[2]
	1988–89	South Alligator River – 384 km^2	#25.2[2]
	1988–89	South Alligator River – 1238 km^2	*52.2[2]

1 – total sediment load yield
2 – suspended load yield
3 – solute yield
3C – solute yield corrected for solute input in precipitation
4 – total terrigenous yield
5 – bedload yield
6 – wash load yield

a – first year after disturbance
b – mean of all post-disturbance years
N – Natural catchment
D – Disturbed catchment
– estimated from limited data
* – estimated from detailed measurements during the Wet season

Duggan (1988) found that there was no significant relationship between suspended sediment concentration and turbidity on Georgetown and Gulungul Creeks during the 1984–85 Wet season. This was explained by the different turbidity readings for coarse and fine sediments of the same concentration. As the mix of grain sizes varies so does turbidity, even if concentration remains constant. Riley (1997, 1998) analysed the same relation for runoff samples on the ERARM waste rock dump. He found that although some of the relationships were statistically significant, they were associated with relatively large errors. However, Curley (1988) reported a highly significant relationship between non-filterable residue and turbidity ($r^2 = 0.87$) for runoff from the waste rock dump and additional data collected by Uren (1990) only improved the relationship ($r^2 = 0.89$). Further data also conformed to the same relationship (Uren 1992). The potential use of turbidity for the continuous monitoring of suspended sediment transport in the Alligator Rivers Region may still be possible and further research is being conducted on the issue.

Magela Creek water is characterised by very low conductivity and low suspended solids concentrations (Hart et al 1986, 1987a). Nevertheless, solutes and suspended solids still exhibit exhaustion as the Wet season progresses (Hart et al 1986, 1987a). The suspended particulate matter of Magela Creek contained approximately 25% organic matter, 15% iron oxide, and the remainder consisted of varying amounts of clay (predominantly kaolinite with some chlorite), quartz and aluminium oxide (Hart & Beckett 1986). Both sediment and solute yields of Magela Creek are low by world standards (Hart et al 1987b), being less than 11.8 and 2.5 t/km^2.yr, respectively (table 4). Roberts's (1991) yields are considered less reliable because they are based on rating curves fitted to limited data and because the bedload field measurements were not as detailed and thorough as those collected elsewhere (cf. Carey 1984, 1985). Nevertheless, the bedload yield is a relatively high proportion (48.6%) of the total sediment load yield, a result consistent with Evans's (1997) and Saynor and Evans's (2000) plot measurements on ERARM's waste rock dump. Duggan (1988) also noted that her suspended sediment samples contained a predominance of fine and medium sand when concentrations exceeded 1000 mg/L.

Detailed characterisation of the colloidal and particulate matter transported by Magela Creek by Hart et al (1993) during a flood on 10–11 April 1986 demonstrated that previous estimates of the particulate fluxes could have been underestimated by as much as 50%. This is likely because approximately equal amounts of suspended particulate matter (>1 µm) (20 t), coarse colloidal matter (between 1 and 0.1 µm) (18 t) and dissolved matter (<0.1 µm) (17 t), and a much smaller amount of fine colloidal matter (between 0.1 and 0.015 µm) (2.6 t) were transported by this flood. Generally a size of between 1 and 0.45 µm is adopted as the distinction between particulates and solutes (Hart et al 1993, Erskine & Saynor 1996a). The coarse colloidal matter is usually included in the dissolved fraction when it is actually particulates. While the combined suspended solids and solute yields of previous work are correct, the partitioning between these two fractions *overestimated* the already low solute yields (Hart et al 1993).

Duggan (1988, 1994) determined the suspended sediment and solute yields of five natural catchments with areas less than 61.9 km^2 in the Kakadu region. These yields were also low, with sediment yields being less than 34.8 t/km^2.yr and solute yields less than 14.0 t/km^2.yr. Solute yields ranged between only 14.5 and 35.2% of the total terrigenous yield. Skeat et al (1996) maintained that feral animal induced erosion increased solute concentrations by a factor of two due to a greater availability of solutes in eroding soils. Denudation rates determined from these sediment yields (mean of about 0.016 mm/yr) are an order of magnitude less than the typical range reported for the seasonally wet tropics by Saunders and Young (1983). The four disturbed catchments exhibited mean suspended sediment yields that were at least one order of magnitude greater than the natural catchments (table 4). However, Duggan (1988, 1994) recorded an exponential decline in suspended load yields with time, following the completion of rehabilitation. Yields decreased by one order of magnitude in year 2 and by two orders of magnitude by year 4. This decline in yields was also accompanied by a marked decrease in the silt and clay percentage of the suspended sediment. Furthermore, unlike the natural catchments, disturbed catchments exhibited sediment exhaustion during the Wet season due to the progressive flushing of the available fine-grained sediment.

Beardsell et al's (1989) and Lancaster's (1990) sediment yields for the South Alligator River catchment confirm Duggan's results (table 4). Fisher Creek had been disturbed by overgrazing of duplex soils and, as a result, sediment yields increased by one order of magnitude over neighbouring catchments (Beardsell et al 1989, East 1996).

There is an inverse relationship between specific sediment yield and catchment area in table 4, as shown in figure 9. Cull et al (1992) previously noted this relationship which they explained by a combination of deposition of part of the sediment load generated in the upstream catchment in the channel and on the floodplain and by lower erosion rates on the flatter slopes of the downstream part of catchments. Cull et al (1992) maintained that the Gulungul Creek sediment yield was very high but such a conclusion is not supported by the larger data set in table 4. They believed that Gulungul Creek was incised and had a number of deep, vertical sided gullies draining into it. This channel erosion was supposed to be the reason for the high yield. Channel erosion alone can certainly produce high sediment yields (Erskine & Saynor 1996b, Erskine & Warner 1999). However, recent ground and aerial inspections by the authors for this project failed to find much evidence of this erosion (see also Saynor & Erskine 1998). Figure 10 shows Gulungul Creek near the tailings dam in June 1997. The channel is not incised and the tributary, a grassed swale at X in figure 10, exhibits a series of shallow flow-aligned discontinuous knickpoints that are not actively eroding.

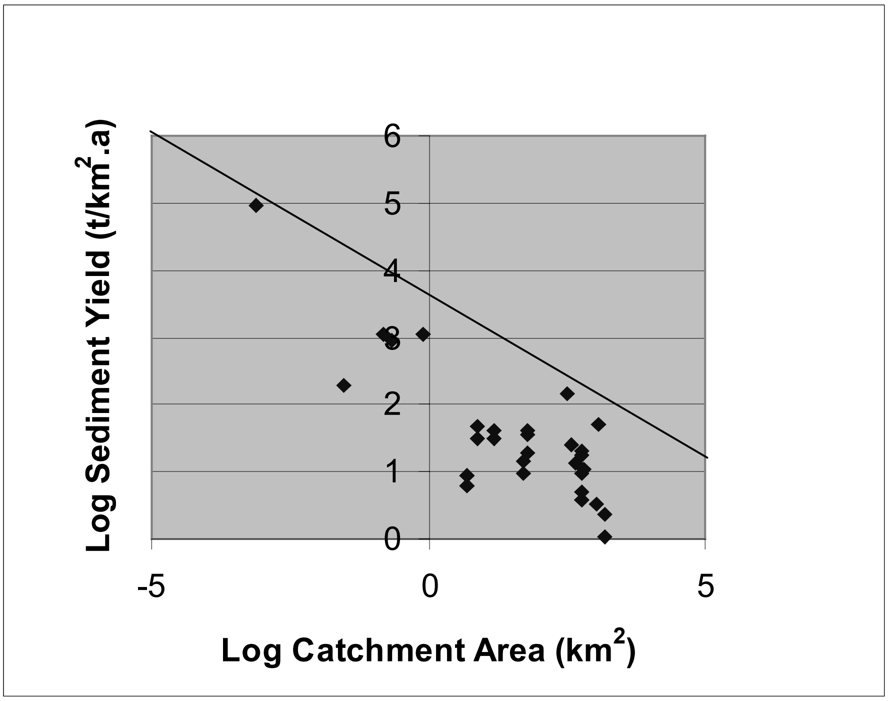

Figure 9 Relationship of specific suspended load, total sediment load and total terrigenous yields versus catchment area for the data in table 4. The envelope line represents the highest sediment yields reported for the Alligator Rivers Region.

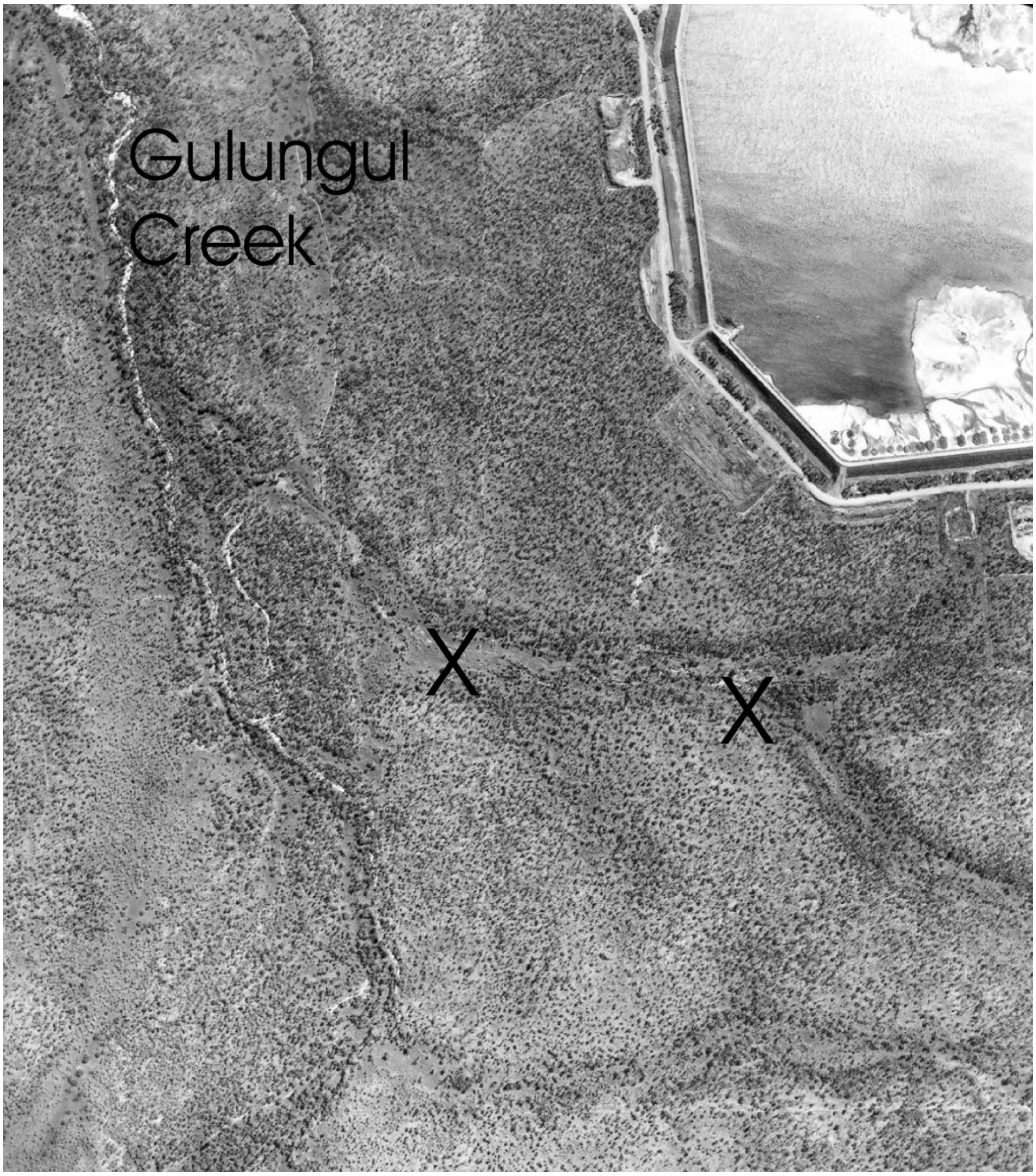

Figure 10 Vertical air photograph of Gulungul Creek and an unnamed right bank tributary near the tailings dam on ERARM (date of photograph: June 1997)

Suspended solids transport in Australian rivers is usually storm dominated (Olive & Rieger 1985, Erskine & Saynor 1996a). Duggan (1988) found that suspended sediment concentration in the natural catchments was best correlated with peak discharge and that suspended sediment transport in the same catchments was dominated by infrequent, large events. There was no pronounced early Wet season peak or marked first flush in the yields (see also Williams 1976). In fact, the seasonal distribution of suspended sediment transport was dominated by large discharges that occurred most frequently in February and March.

Williams (1976) also found that over 90% of the suspended sediment yield on the Adelaide River was transported during February and March. Duggan (1988, 121) concluded that:

> On the basis of available data, the low probability events not included in the record (greater than 1:100 yr.) could be expected to transport *disproportionately* ***high*** *loads of suspended sediment* (our emphasis).

She also noted that:

> The erosion studies in natural catchments suggest that *extreme rainfall events will cause extreme rates of soil los*s (our emphasis) (Duggan 1988, 247).

These findings were supported by Evans's (1997) plot studies and are consistent with those reported elsewhere in Australia (Olive & Rieger 1985, 1986, Erskine & Saynor 1996a,b). According to Olive and Rieger (1985), they reflect the greater flow variability of Australian rivers in comparison to those in the rest of the world, except southern Africa, that has been documented by Finlayson and McMahon (1988) and McMahon et al (1992). However, flow variability during the Wet season in the Alligator Rivers Region is not as high as elsewhere in Australia. The marked difference in variability between the Wet and Dry seasons seems to be more important in the seasonally wet tropics.

Riley (1994b, 1995c) used the measured denudation rates in the Alligator Rivers Region to estimate the erosion rate of the Nabarlek uranium mill tailings containment cover. From his review of the available information, it was concluded that a conservative denudation rate of 0.05 mm/a would apply to the containment cover. This estimate is less than the combined soil creep and slopewash sediment yields of Williams (1973, 1976) and is two orders of magnitude less than the highest rates for disturbed areas in table 2. To incorporate a safety factor in his estimated denudation rate, Riley (1994b, 1995c) doubled the above estimate, which is still one order of magnitude less than the highest rates in table 2. Nevertheless, the highest denudation rate would still not remove more than half of the waste rock cap unless severe gullying occurred. Riley's (1994b, 1995c) detailed assessment of gullying indicated that this was unlikely but Evans's (1997, Evans et al 1998) SIBERIA modeling suggests the opposite.

An envelope line has been drawn above the highest sediment yields in figure 9. This indicates the maximum recorded sediment yields for a given catchment area in the Alligator Rivers Region. If the interpolated value for a catchment area of 4 km^2 is applied to the rehabilitated landforms on ERARM, then the estimated maximum sediment yield over the 1000 years structural life is 12.7×10^6 t. As expected, this amount is much less than that predicted using the maximum recorded soil erosion rate (20.4×10^6 t) in section 3 because of the larger catchment area. For design purposes, the soil erosion estimate combined with a factor of safety should be used because it is more conservative (ie it ensures greater landform stability).

5 Fate of particulates

5.1 Mine site tributaries

The mine site tributaries of concern are Gulungul, Djalkmarra, Coonjimba and Georgetown Creeks near ERARM (fig 1). These creeks will be the first to receive sediment generated on the rehabilitated mine site and act as a buffer for Magela Creek. Djalkmarra and Coonjimba Creeks are impounded by the embankment for the mine access road and retention pond 1, respectively. Therefore, there is a low potential for the dispersion of mine site generated sediment through these two creeks for as long as these structures remain intact. The tailings dam is located within the catchment of a right bank tributary of Gulungul Creek (fig 10).

The possible release and dispersion of tailings from ERARM have been identified as potential hazards (Pickup et al 1983, 1987, Waggitt & Riley 1994, Rippon & Riley 1996) but the erosion and dispersion of cap material used to form the artificial landforms of the rehabilitated mine site are now considered more important (Willgoose & Riley 1993, 1998, Evans 1997, Evans et al 1998). The two main sources of particulates and solutes to the mine site tributaries are *tailings* and *waste rock, low grade ore* and *their weathering products* (Riley & Waggitt 1992). Waste rock has less than 0.023% uranium (U_3O_8) content. Pickup et al (1983, 1987) presented a single partial grain size distribution of Ranger tailings. Except for a very small coarse tail of medium sand, the bulk of the tailings were fine and very fine sand, silt and clay (Wentworth size fractions). Cull et al (1992) reported that the tailings consisted of 32 ± 9% sand, 52 ± 8% silt and 16 ± 11% clay. The tailings are neutralised after processing, but the solution may contain a variety of toxic materials, including high solute loads of SO_4^{2+} (for example $MgSO_4$), kerosene, ammonia, soluble uranium and other heavy metals (Pidgeon 1982). Riley (1992, 47) found that the surface waste rock material was dominated by gravels and sands (in that order), and had very low silt and clay contents (<9%) (Wentworth size fractions). Nevertheless, runoff from the waste rock dump contained more silt and clay than were present in the surficial material (Riley 1992, 1995b, Riley & Gardiner 1991). The waste rock weathers relatively rapidly, producing clay and finer gravel (Riley 1995b,d). Iron and magnesium are present in particulate form in the suspended sediment eroded from the waste rock (East et al 1994). Oxidation of the sulfide in the schist occurs throughout the year and epsomite ($MgSO_4$) is flushed by the early Wet season storms (East et al 1994). Run-of-mine waste rock produced lower sulfate concentrations than the schist and more than 70% of the solute load is comprised of magnesium and sulfate. Weathering of dolomite produces bicarbonate which partially neutralises the acidic rainwater and the products of pyrite oxidation.

The soil loss and sediment yield data (tables 2 & 4) indicate that disturbed areas, particularly mine sites, can generate high sediment yields in the Alligator Rivers Region. The physical impacts of deposition of a proportion of this eroded sediment are important. Toxicity effects are not considered here (see Rippon & Riley 1996). All of the eroded material will not be transported rapidly off the mine site and into these creeks (Duggan 1988, Evans 1997), particularly as the gravels are less mobile under overland flows than the other size fractions of the waste rock (Riley 1992, 1995b, Riley & Gardiner 1991). Duggan (1988, 1994), as outlined above, found significant sediment storage on natural slopes during her erosion pin measurements. Basal slope concavities are formed by deposition of at least some of the sediment eroded from upslope and are common in the Alligator Rivers Region (East et al 1989a, 1994). Evans et al (1999) also observed small scale litter and coarse organic debris dams (Mitchell & Humphreys 1987), trapping sediment and fine particulate organic matter on burnt, vegetated plots on ERARM’s waste rock dump. Pickup et al (1987) concluded that there is only limited opportunity for the dispersion of eroded sediment into the mine site tributaries because the natural slopes have a low gradient, high infiltration capacity, surface gravel lags and few rills. The rehabilitated slopes should mimic these features. SIBERIA also predicts significant local deposition on the rehabilitated mine site (Willgoose & Riley 1993, 1998, Evans 1997, Evans et al 1998). Sand and gravel sized sediment will not be transported far during individual events but fine sediment deposition requires very hydraulically rough conditions (ie vegetated areas) or essentially still water (ie lakes, billabongs and wetlands).

The sediment delivery ratio refers to the percentage of the annual gross erosion that is measured as the sediment load at a catchment outlet (Walling 1983). Sediment delivery ratios of less than 10% have been measured in large agriculturally disturbed catchments and demonstrate that sediment storage is often a more significant geomorphic process than sediment transport (Walling 1983, Trimble 1983). There is an inverse relationship between sediment delivery ratio and catchment area (Walling 1983, 1984), so that sediment storage is *usually* more significant in larger catchments, especially those that have been disturbed by land use changes (Trimble 1983). Nevertheless, Evans (1997, Evans et al 1998) found that

SIBERIA predicted that there would be local but large scale deposition in valleys (up to 14.8 m) on the ERARM rehabilitated landforms over the 1000 years structural life. One fan was about 440 m long and up to 9 m thick, and stored 70 290 t of sediment (Evans 1997, Evans et al 1998). SIBERIA also predicted cyclical deposition and erosion of these fans, as has been documented on natural fans in sandstone catchments (Scott & Erskine 1994). Duggan (1988) determined sediment delivery ratios of 0.41, 0.28 and 0.44 for Ranger (catchment area of 0.22 km^2), Nabarlek (catchment area of 0.78 km^2) and Jabiru Tributary 1 (catchment area of 0.15 km^2) catchments, respectively. Therefore, not all of the sediment generated on the rehabilitated mine site will be delivered directly to the mine site tributaries but *most* will be temporarily stored on the mine site (Warner & Wasson 1992). However, the residence time of the stored sediment is unknown because the deposited sediment can be subjected to repeated phases of re-entrainment, transport and storage, particularly by discontinuous gullying (Erskine & Melville 1983a).

Duggan's (1988) sediment budget for Ranger Tributary for year 2 of her measurements is shown in figure 11. Erosion from embankments and gullies produced 17% of the erosion from 8% of the area. Disturbed lowland slopes generated 83% of the erosion from 92% of the area. Sediment storage accounted for 54% of the eroded sediment (Duggan 1988). The suspended sediment was enriched in silt and clay in comparison to the surface soils immediately following disturbance (see also Riley 1992, 1995b, Riley & Gardiner 1991) but then declined in subsequent years. Gullies up to 1 m deep formed on slopes of less than 2° in one Wet season during construction activities. Similarly, rills were only found where the soil surface had been disturbed. It must be also be emphasised that the spatial distribution of sediment sources and their significance can change on at least an annual time scale (Erskine & Saynor 1996a).

Cull et al (1992) constructed a sediment budget for Gulungul Creek. This budget is not included here because:

1. Sediment yields and not soil loss rates were used to estimate mine site erosion (see section 4);
2. There are errors in the adopted sediment yields (see section 4);
3. Sediment yields for natural catchments and not disturbed catchments were used. As a result, the adopted sediment yields are too low (see section 4);
4. The significance of channel erosion seems to have been overestimated (see section 4);
5. Inappropriate sediment delivery ratios were used (cf. Duggan 1988); and
6. No account was taken of the sediment storage capacity of backflow billabongs (see below).

Possible sediment budgets for 1000 years structural life of the rehabilitated mine site have been constructed for the soil loss estimated in section 3 and the sediment yield estimated in section 4 (table 5). Three sediment delivery ratios have been used. The largest and smallest values coincide with the range evident in the large data set compiled by Walling (1983, 1984) for a catchment area of 4 km^2. The intermediate value was obtained by Duggan (1988) for her largest catchment. The lower sediment delivery ratios are more appropriate for ERARM rehabilitated mine site.

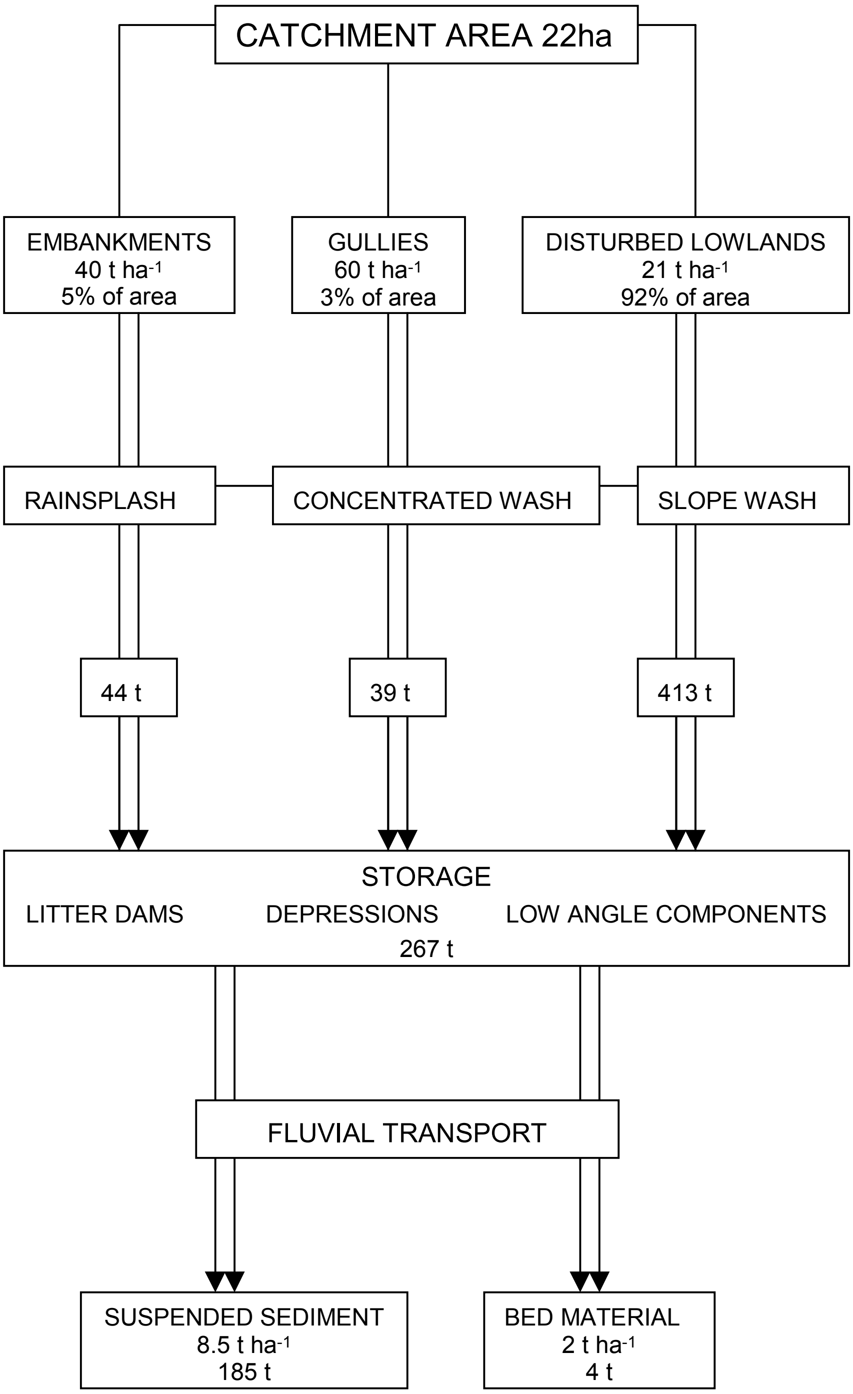

Figure 11 Duggan's (1988) sediment budget for Ranger Tributary for year 2 of measurements

Table 5 Possible sediment budgets for ERARM, the mine site tributaries and Magela Creek for the 1000 years structural life of the rehabilitated mine site. Estimated errors for each term are at least 30–40%. See section 3 for the estimated soil loss for scenarios 1 to 3, inclusive and see section 4 for the estimated sediment yield for scenarios 4 to 6, inclusive. Scenario 4 is the most likely one to occur following mine rehabilitation.

Scenario	1	2	3	4	5	6
Estimated total soil loss/sediment yield from mine site (t)	20.4×10^6	20.4×10^6	20.4×10^6	12.7×10^6	12.7×10^6	12.7×10^6
Estimated sediment delivery ratio	0.28	0.24	0.50	0.28	0.24	0.50
Estimated sediment storage on rehabilitated mine site (t)	14.7×10^6	15.5×10^6	10.2×10^6	9.1×10^6	9.6×10^6	6.35×10^6
Estimated sediment yield from rehabilitated mine site (t)	5.7×10^6	4.9×10^6	10.2×10^6	3.6×10^6	3.1×10^6	6.35×10^6
Estimated sediment storage in mine site tributaries (t)	3.5×10^6	3.5×10^6	7×10^6	3.5×10^6	3.1×10^6	3.5×10^6
Estimated sediment storage in Magela Creek sand anastomosing zone (t)	0.5×10^6	0.5×10^6	1×10^6	0.1×10^6	0	1×10^6
Estimated sediment storage in lower Magela creek floodplain (t)	1.7×10^6	0.9×10^6	2.2×10^6	0	0	1.85×10^6

Pickup et al (1983, 1987) noted that small tributaries near ERARM are frequently small, poorly defined and sometimes discontinuous and that they all discharge into backflow billabongs at the junction with Magela Creek (Riley & Waggitt 1992). They emphasised that the stability of these channels and their likely response to changes in runoff and sediment delivery due to the construction of rehabilitated landforms in their catchments, needed investigation. We agree. This information is important for predicting the transmission, dispersion and storage of any contaminated particulate material by sediment transport. Warner and Wasson (1992) noted that sediment would move as event-driven pulses both within and between different fluvial landforms from ERARM to Magela Creek through the mine site tributaries. However, they did not attempt to determine the nature of this sediment routing. Cull et al (1992) found that, on Gulungul Creek, the channel and natural levees are composed mostly of sand and that silt and clay contents are low but at their greatest on the floodplain. Channels are transit zones for sand. However, they also noted that unchannelled reaches are present near the mine site (see fig 10) and that the surface sediments contain much higher silt and clay contents. Similar results have been found in sandstone catchments in south-eastern Australia (Erskine & Melville 1983a, Melville & Erskine 1986). Therefore, some fine sediment storage will occur in the unchannelled valleys and on the floodplain.

There is little information on sediment movement, sediment storage and the time lags involved for the mine site tributaries. Pickup et al's (1983, 1987) recommended studies of monitored cross sections, analogue testing, tracer investigations and sediment budgets have not all been undertaken. The fluvial dispersion of radioactive mill tailings at the old Northern Hercules Mine at Moline was completed to provide a possible analogue (Pickup et al 1987, East et al 1988). This work demonstrated that:

1. Exposed tailings eroded at much greater rates than local soils but the rate declined over time;
2. High specific radioactivity was closely associated with the fine sediment fraction;

3. Low energy depositional environments accumulated the most tailings and the highest dose rates because of their fine-grained nature; and
4. Dose rates decreased with distance downstream of the mine site (East et al 1988).

Tailings should not be eroded at ERARM if there is a sufficient depth of cap material (Evans 1997, Evans et al 1998). The geomorphology and sedimentary environments of the mine site tributaries have not been determined in any detail. Duggan's (1988, 1994) detailed work addressed the dynamics of suspended sediment transport and suspended sediment yields for a short period at a few gauging stations on mine site tributaries (table 4). While this work is thorough and important, it is still necessary to determine the physical connectivity of the river channels, the factors controlling their dynamics and the nature of sediment movement and storage through the channel network. Discontinuous channels cause substantial sediment deposition and medium term storage (Schumm 1961, Patton & Schumm 1981, Erskine & Melville 1983a, Melville & Erskine 1986). Indeed, Erskine (1996b) has found examples of buried telegraph poles on discontinuous channels draining sandstone catchments in the Clarence-Moreton Basin. However, such disconnected channels are also unstable and are subjected to repeated phases of valley-bottom gullying (Schumm 1961, Patton & Schumm 1981, Erskine & Melville 1983a, Melville & Erskine 1986). The potential for valley-bottom gullying on the mine site tributaries has not been determined. The approaches used by Riley and Williams (1991) or Scott and Erskine (1994) could be used to assess the probability of gully initiation.

Approximate measurements of channel, floodplain and unchannelled areas downstream of ERARM and upstream of Magela Creek were made using all available information (for example, Nanson et al 1990, 1993, East et al 1993). Then potential depths of stored sediment eroded from the rehabilitated mine site over the 1000 years structural life, were estimated. The results of Pickup et al (1983, 1987), East et al (1988) and Nanson et al (1990, 1993) and the authors' research on sedimentation in sand-bed channels and their floodplains (Erskine & Melville 1983a, 1983b, Melville & Erskine 1986, Erskine 1986, 1993, 1994a,b, 1996a, Erskine & Saynor 1996b) were used as guides. It was assumed that the stored sediment would be deposited as a downstream thinning wedge and that sand would be deposited in the channel bed (γ = 1.1 t/m^3) and silty sand on the floodplain and in unchannelled valleys (γ = 1.6 t/m^3). This approximate sediment budget indicates that about 2.3×10^6 t will be deposited in the channel and floodplain of the mine site tributaries downstream of ERARM. A larger mass will be stored for scenario 3 because of the high sediment yield from the rehabilitated mine site (table 5). There is a large error associated with these values because the final sediment depths are crude estimates.

Fox et al (1977) and Hart and McGregor (1980) were the first to call the terminal wetlands on the mine site tributaries, 'backflow billabongs', because water often flows from Magela Creek into the tributaries (ie backflow). Backflow billabongs are equivalent to the earlier defined 'blocked valley lakes' of Blake and Ollier (1971) and the 'backstow lakes' of Wilhelmy (1958). Hart and McGregor (1980) speculated that backflow conditions would tend to deposit fine sediments and organic material in the billabongs, whereas tributary flows would tend to flush them. However, as first noted by Galloway (1976), reverse sandy deltas (fig 12) often extend into the wetlands from the main channel, disproving Hart and McGregor's (1980) simplistic notion of water circulation and sediment transport (Saynor & Erskine 1998).

Figure 12 Reverse sandy delta from Magela Creek extending into Gulungul Billabong. This indicates that the billabongs have a high sediment trap efficiency, even for silt and clay. Therefore, any sediment derived from ERARM and transported into the mine site tributaries will be deposited and at least temporarily stored in the backflow billabongs.

Thomas and Hart (1984) and Nanson et al (1993) found that sandy plugs (ie reverse deltas) deposited by Magela Creek dam the backflow billabongs on the lower section of the mine site tributaries. The river bed of Magela Creek lies 1.5 to 2.0 m above the floor of the backflow billabongs (Nanson et al 1993). Hence the channel bed dams the tributary, not the levee, as suggested by Galloway (1976), Hart and McGregor (1980), Walker and Tyler (1984) and Pickup et al (1987). Furthermore, these sandy plugs have deflected the billabong outlet channels down the left bank valley side in the form of a deferred tributary junction or a yazoo stream (Pickup et al 1987, Nanson et al 1993). Clearly, Magela Creek transports more sediment and has aggraded more rapidly than the tributaries, similar to the Macdonald River near Sydney (Henry 1977, Erskine 1986).

Recent work on similar blocked valley lakes in a sandstone catchment near Sydney has demonstrated that these lakes trap and store essentially all of the inflowing bedload and most of the inflowing suspended load (Marshall 1997, Borgert 1998). While Nanson et al's (1993) stratigraphy of Georgetown and Coonjimba Billabongs is highly generalised, it does show extensive dark clays separating the sandy bedload deposits of the tributaries from those of the main stream in Coonjimba Billabong. The sand shown by Nanson et al (1993) flooring Georgetown Billabong is in fact just a small sill separating two mud basins and does not cover the whole billabong (Thomas & Hart 1984). Lacustrine sediments of organic-enriched silt and clay dominate in most backflow billabongs (Thomas et al 1981, Thomas & Hart 1984).

This indicates that there has been active flow and bedload transport from Magela Creek into the backflow billabongs and that very little, if any, sand has been transported through the billabongs into Magela Creek from the tributaries to date.

The backflow billabongs are shallow (1–3 m) with shelving banks and with largely vegetated, organic clay or silt bottoms (Hart & McGregor 1980, Thomas et al 1981, Thomas & Hart 1984, Finlayson et al 1994). Woods (1995) presented long-term water quality data for Gulungul Billabong but unfortunately did not discuss depth profile results. However, thermal stratification, and hypolimnetic anoxia and reducing conditions have been recorded in these backflow billabongs during the early Wet season (Hart & McGregor 1980, 1982). Hart and McGregor (1980, 1982), Walker and Tyler (1984) and Walker et al (1984) found that thermal stratification developed during the day and either overturned at, or rarely persisted during the night. Marked temperature differences between surface and bottom waters (10.5°C) were recorded in water depths of only 0.7 m in the turbid Gulungul Billabong (Hart & McGregor 1980, 1982). Very low dissolved oxygen contents (3% saturation) and reducing conditions (E_h = -130 mV) were measured as early as 1000 hours in Georgetown Billabong (Hart & McGregor 1980, 1982). Irrespective of thermal stratification, anoxia occurs for about one month when macrophytes decompose as floodwaters recede (Walker & Tyler 1984a). Such conditions as well as reducing conditions in the bottom sediments can cause the release of sediment-bound contaminants and nutrients, as suggested by some of Hart and McGregor's (1980, 1982) results. Acid stratification was also briefly recorded in all backflow billabongs (Hart & McGregor 1980, 1982) during the first flush of the Wet season but was not investigated in the detail that it warranted (for example, see Sammut et al 1994). Turnover or holomixis of such highly stratified water has been recorded, sometimes during storms, in the Alligator Rivers Region (Walker et al 1984, Townsend 1994).

Walker and Tyler (1984) also found that there was a massive increase in turbidity during the Dry season in the early 1980s, which was sufficient to curtail primary production at a time of nutrient abundance. Suspended solids concentrations have declined in the backflow billabongs in recent years following the removal of feral buffalo, pigs and cattle by the mining company (Woods et al 1994). It is not known if primary production has consequently increased. Nevertheless, disturbance of bottom sediments should also be avoided in the future so as to reduce the likelihood of mobilising sediment-adsorbed contaminants.

The references on backflow billabongs cited above have been used to estimate the potential sediment storage capacity of the billabongs. Assuming that the billabongs would be at least initially infilled with fine sediment and that the bulk density of the lacustrine sediments is 1.1 t/m^3, about 1.2×10^6 t could be stored in the billabongs. Therefore, about 3.5×10^6 t would be stored in the mine site tributaries, except for the high sediment yield of scenario 3 (table 5). Clearly the bulk of this sediment would not be delivered to the mine site tributaries for some time after mine closure.

The above work indicates that the sediment generated on the rehabilitated landforms at ERARM will not be transported rapidly to Magela Creek. Instead significant local storage will occur on the mine site and immediately downstream. Sands will be repeatedly stored in, and reworked from, the alluvium of the tributary channels and floodplains. However, the immediate sink for both sand and mud (ie silt and clay) will be the backflow billabongs at the junction of the tributaries with Magela Creek. Essentially no sand and only minor amounts of silt and clay will be exported from the mine site tributaries and into Magela Creek, *until this deposition greatly reduces the storage capacity of the billabongs*. Much greater attention needs to be directed at these tributaries and a geomorphic monitoring program should be implemented. Monitoring should include discharge, sediment transport, water quality, channel and floodplain surveys, channel and floodplain sediment characterisation, and the seasonal and inter-annular geomorphic, hydrological and limnological behaviour of the backflow billabongs. Detailed assessment of channel changes from all available vertical aerial photography should also be conducted to determine the medium term behaviour and dynamics of the mine site tributaries (Pickup et al 1987). The probability of gully initiation on unchannelled reaches near the mine site also needs to be defined because gullies would remobilise temporarily stored sediment.

5.2 Magela Creek anastomosing sand zone

All of the mine site tributaries discharge into the anastomosing (multi-channelled) sand zone of Magela Creek that is located downstream of the upper bedrock gorge but upstream of the extensive wetlands between Mudginberri and the East Alligator River, which are discussed below. The anastomosing channels are laterally stable, sand-floored, steep-sided with a dense root mat and are separated by islands with well defined marginal levees (Nanson et al 1993). Bankfull discharge is only about 40 m^3/s and the floodplain is inundated for long periods during the Wet season (Nanson et al 1993). Magela Creek next to ERARM flows along the western side of its valley and is flanked on the east by extensive Pleistocene alluvium and palaeochannels. Despite numerous comments to the contrary in the literature, the channel is *not* a braided stream because of:

- the permanent nature of the islands separating the individual channels;
- the absence of lozenge-shaped, sandy braid bars;
- apparent channel stability due to the lack of bank erosion; and
- the long individual channels between points of bifurcation and confluence (Nanson et al 1993).

The ancestral Magela Creek during lower sea levels eroded its bed producing a trench cut into Pleistocene alluvium and bedrock (Nanson et al 1993). This trench was progressively backfilled during the mid to late Holocene. The medium to coarse sand channel-fill is 8–12 m deep, 200–400 m wide and prograded progressively downstream from the North Arm junction, with a basal date of 7260 ± 90 yr at the North Arm but 4950 ± 260 yr at Mudginberri (Nanson et al 1993). Downstream progradation was followed by an accelerating rate of vertical accretion (Roberts 1991). The contemporary progradation rate of the sand into Mudginberri billabong is 7.5 m/yr (Nanson et al 1993) but sandy sediments also extend much further downstream (Thomas & Hart 1984). The alluvial trench upstream of Mudginberri has now been essentially infilled with sand and any further vertical accretion will start to bury much older marginal alluvium (Nanson et al 1993). At about 6 ka, Magela Creek discharged into a relatively narrow tidal estuary about 6–7 km upstream of Mudginberri which had been converted to freshwater by about 4 ka (Clark et al 1992b).

Nearly all of the silt and clay, and most of the sand supplied from the mine site tributaries will be transported through this zone to the lower floodplain. Very minor amounts of silt and clay will be deposited on the floodplain and some sand will be deposited in the bed and on the levees and the floodplain as splays. This zone is a transport reach characterised by relatively minor sediment storage (Cull et al 1992). Assuming that 0.1 m of sediment would be uniformly stored over the current channel and floodplain, less than 1×10^6 t would be stored in the anastomosing section of Magela Creek. For scenario 5, no sediment would be exported from the mine site tributaries to Magela Creek (table 5).

5.3 Lower Magela Creek floodplain

The lower floodplain starts at Mudginberri Billabong and extends to the East Alligator River. While this area is being treated as a single unit, there are longitudinal changes in landforms (the Mudginberri Corridor, Upstream Basin, Central High and Downstream Plain of Warner & Wasson 1992). The natural levee of the East Alligator River does not impound the lower reaches of Magela Creek (Warner & Wasson 1992) and the extensive wetlands were formed at least in part by sedimentation raising the Magela Plain above tidal inundation (Clark et al 1992b).

Cull et al (1992) investigated the surface sediment texture of the lower floodplain sediments and found that sand is largely restricted to the Mudginberri Corridor and the proximal part of the Upstream Basin. However, clay contents did *not* increase progressively downstream, indicating that side tributaries also input sediment to the floodplain. The bottom sediments of the billabongs indicate that sands dominate in the channel billabongs of the Mudginberri Corridor (Mudginberri Billabong, Y-Shape Billabong, Island Billabong, Three-Croc Billabong and Boomerang Billabong, Thomas et al 1981, Thomas & Hart 1984). However, silt and clay dominate in the downstream floodplain billabongs (Hidden Billabong, Leichhardt Billabong, Jabiluka Billabong and Nankeen Billabong, Thomas et al 1981, Thomas & Hart 1984). Organic-enriched, clay flocs certainly formed in the bottom of the channel billabongs during the Dry season but they were remobilised during the next Wet season (Thomas & Hart 1984).

Hart et al (1987b) calculated an input-output budget for the lower Magela Creek floodplain or backplain for the 1982–83 Wet season. They found:

> Broadly, the Magela floodplain appears to be a net source of the major ions (sodium, potassium, calcium, magnesium, chloride, sulfate and bicarbonate) and a net sink for suspended solids and nutrients (total phosphorus, nitrate-N, ammonia-N). The data suggest that the floodplain is also a net sink for the trace metals copper, lead and zinc, and uranium, but in these cases the amounts transported are quite small and the uncertainties rather large.

They estimated that 5400 t of suspended solids entered the floodplain, 1700 t (69% reduction) were exported and 3700 t were deposited in the floodplain. However, there are large error terms associated with these estimates.

Figure 13 shows the mean annual suspended sediment fluxes for the lower reaches of Magela Creek that were calculated by Cull et al (1992). Of the 9900 t/a that is delivered to the plain, only 3600 t/a are exported to the East Alligator River. This represents a 64% reduction in the inflows due to deposition and storage. However, there are also large error terms associated with these calculations (fig 13). Despite the difference in the magnitude of the estimated sediment loads by Hart et al (1987b) and Cull et al (1992), the percentage of the inflowing sediment trapped in the Magela plain is similar for both data sets (69 and 64%, respectively). Sediment radionuclide concentrations of Magela Creek and the plain were interpreted by Cull et al (1992) to mean that about 90% of the particulate matter from Magela Creek is deposited in the first 18 km of the plain.

Cull et al (1992) also attempted to use ^{137}Cs as a tracer of sedimentation on the lower Magela floodplain. They encountered many problems with the technique and were only able to calculate an upper limit to overall sedimentation rate of <0.9 mm/yr.

Cull et al (1992) then conducted detailed analyses of the natural U and Th series radionuclides in flood water samples collected between 19 and 21 February 1985 and on 10 April 1986. They concluded from this technique that during the last 100 years there has been little but not zero loss of suspended sediment from the floodplain. A small but inter-annually variable proportion of particulates delivered to the floodplain is exported but the proportion could not be quantified with the then available data.

Subsequent work based on naturally occurring radionuclides by Murray et al (1993) found that all of the inflowing particulate load from Magela Creek and adjacent tributaries is retained by the floodplain. Similarly, a substantial fraction of solutes and colloids is also trapped.

The main conclusion to be drawn from the above work is that the lower Magela floodplain is a relatively efficient sediment and solute trap. The remaining sediment and solutes eroded from the ERARM rehabilitated mine site would be deposited and stored in this floodplain (table 5). For scenarios 4 and 5, no sediment would be supplied to the lower floodplain. The largest sediment storage mass equates to a sediment depth of 10 mm if the material is uniformly distributed over the 220 km^2 floodplain. Sediment depths will be greater at the upstream end in the Mudginberri Corridor. However, the lower Magela floodplain will be the last area to receive mine-derived sediment. The rate of sedimentation is likely to be closer to the rates of clay deposition of 0.19 and 0.20 mm/yr determined by Clark et al (1992a) by the ^{226}Ra excess method in the Mudginberri Corridor. Cull et al (1992) estimated a mean deposition rate of 0.23 mm/yr based on all radiometric methods. Thomas and Hart (1984) calculated a sedimentation rate of 0.43 mm/yr in the Mudginberri Corridor based on a single radiocarbon date. Little but more likely no mine-derived sediment will reach the East Alligator River.

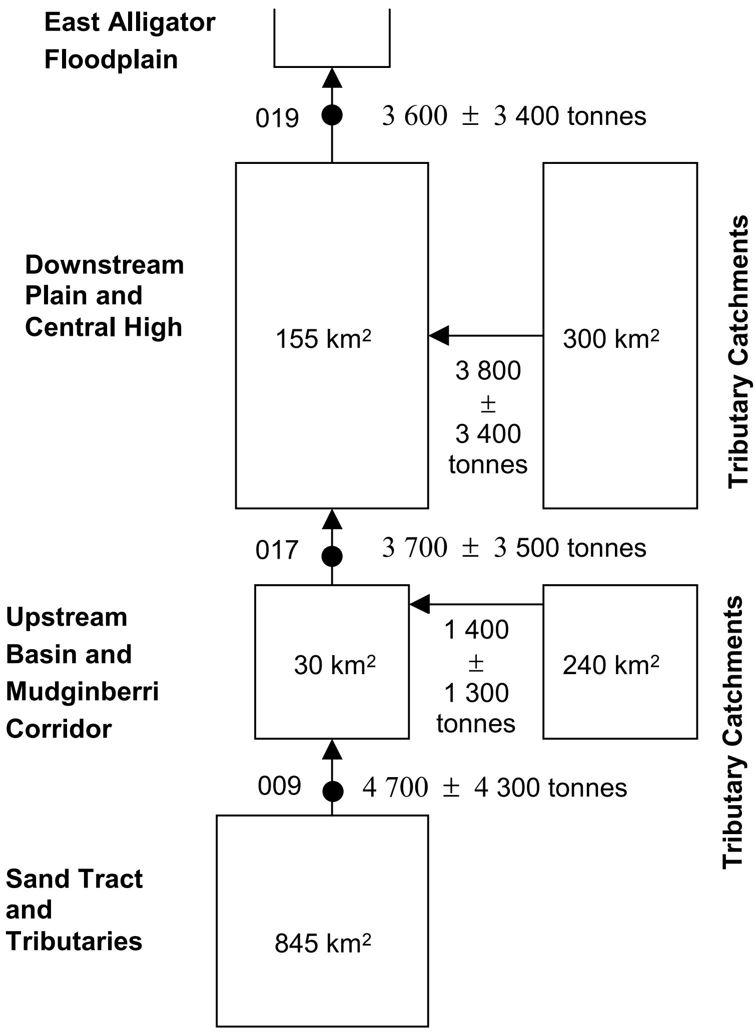

Figure 13 Mean annual fluxes of suspended sediment through the Magela Plain (Cull et al 1992)

We believe that scenario 4 in table 5 is the most reliable predictor of future sediment dynamics for the 1000 years structural life of the rehabilitated mine site. According to this scenario, only 1×10^5 tonnes of sediment of the estimated 12.7×10^6 tonnes generated on the rehabilitated mine site will be exported from the mine site tributaries to Magela Creek. Clearly, the lower floodplain would not be impacted under this scenario. Furthermore, implementation of locally meaningful soil conservation works may also decrease the soil loss rates on the rehabilitated mine site below that specified in table 5. Soil retained on the mine site will not cause off-site problems. However, scenario 4 highlights the significance of the mine site tributaries and their associated backflow billabongs as long-term sediment storages of mine-derived particulates. The other five scenarios are proposed so that the full range of potential sediment impacts can be meaningfully considered during planning for mine decommissioning and rehabilitation.

6 Magnitude and frequency of extreme floods and their erosional and depositional effects

The purpose of this section is to demonstrate that although extreme storms and floods can occur in the Northern Territory (Kennedy & Hart 1984, Bureau of Meteorology 1999), no such events have been recorded at ERARM since the start of mining and, therefore, the erosional and depositional effects of such events are largely unknown from observations and monitoring programs.

6.1 Extreme rainfall

The Kakadu region is included in the summer rainfall–tropical climatic zone which is characterised by heavy periodic rains and generally hot and humid conditions from November to March, and essentially dry and mild to warm conditions from April to October (McQuade et al 1996). At Jabiru, 92% of the average annual rainfall (1460 mm for the period 1971−1992) is recorded during the Wet season months of November to March (McQuade et al 1996). More recent work by Chiew and Wang (1999) found that the mean annual rainfall for the period 1971−1998 was 1500 mm at Oenpelli and 1480 mm at Jabiru. For the complete period of record at each site, the mean annual rainfall is 1397 mm and 1483 mm at Oenpelli (1911−1998) and Jabiru Airport (1972−1998), respectively (Bureau of Meteorology 1999). Rainfall variability in the summer rainfall-tropical climatic zone is low to moderate but high daily totals are recorded during tropical cyclones. One cyclone per year on average affects the Northern Territory coast (McDonald & McAlpine 1991). Riley (1991) analysed the pluviometer records for Jabiru Airport between 1971 and 1990 and found that there were 16 277 hours of missing data and only 8398 hours of accumulated data. Of the 656 storms investigated, only 10 occurred between May and September. On average, there were 5−6 days between storms during the Wet season and the median storm duration was 3−5 hours. The maximum recorded 30 min rainfall was 91.5 mm in November 1984 (Riley 1991). However, the large amount of missing data indicates that these values may not be representative of long-term conditions.

M^c^Gill (1983) found that the original rainfall designs used in the Alligator Rivers Region underestimated the magnitude of extreme rainfall events. McQuade et al (1996) noted that the largest 24-hour total at Jabiru was 164 mm on 26 January 1993. However, McGill (1983) recorded 306 mm at Ranger Plant site on 3 February 1980. McQuade et al (1996) also noted that 250 mm were recorded in 12 hours at Darwin during Cyclone Tracy, 426 mm were recorded in 24 hours at Maningrida during Cyclone Max and 270 mm were recorded in

24 hours at Point Stuart during Cyclone Gretel. McGill (1983) tabulated the extreme daily rainfalls recorded in the Top End. Four events were listed with higher daily rainfall than at Maningrida during Cyclone Max. These storms were 544 mm at Roper Valley Station on 15 April 1963, 513 mm at Angurugu on 28 March 1953, 510 mm at Port Keats Mission on 18 February 1976 and 507 mm at Yirrkala Mission on 12 January 1958. Indeed, Angurugu has experienced at least four events with daily rainfall greater than the 306 mm at Ranger Plant site. These were the aforementioned storm of 28 March 1953 plus 425 mm on 15 March 1976, 363 mm on 9 April 1931 and 355 mm on 31 March 1923 (McGill 1983).

The maximum daily rainfall during the January 1998 flood at Katherine was relatively small, despite Wasson et al's (1998) claims to the contrary. For example, maximum falls were 220.8 mm at Katherine Airport on 26 January 1998, 239 mm at Tindale RAAF Base on 27 January 1998 and 262 mm at Eva Valley on 27 January 1998. Baker and Pickup (1987) noted that the then maximum recorded 24 hour rainfall at Katherine was 234 mm in January 1910. Bureau of Meteorology (1999) found that the January 1998, 24 hour rainfall at Katherine Airport was only the 4th highest on record and that the 48 and 72 hour values of 380.6 mm and 398 mm, respectively were the 2nd highest on record. Furthermore, McGill's (1983) list of extreme daily rainfalls was never intended to be exhaustive, although it was recognised that the Top End was meteorologically fairly homogeneous (Kennedy & Hart 1984). Clearly there has *not* been an extreme storm recorded at ERARM since the mine started operation.

McGill (1983) cited a probable maximum precipitation for a duration of 24 hours of 600 mm for the Magela Creek catchment and a world maximum daily rainfall of 1920 mm. Kennedy and Hart's (1984) more recent work found that the probable maximum precipitation of 24 hour duration for a 100 km^2 catchment in the Alligator Rivers Region is greater than 1200 mm and is greater than 1100 mm for a 1000 km^2 catchment. However, the probability of occurrence in a year of these storms is 1:10 million and 1:1 million, respectively (Kennedy & Hart 1984). In comparison, the maximum recorded 24 hour rainfall in Australia for a 100 km^2 catchment is about 850 mm and about 790 mm for a 1000 km^2 catchment (Kennedy & Hart 1984). Recent work by the Bureau of Meteorology (1999) found that the 24 hour probable maximum precipitation estimated by the Generalised Tropical Storm Method for a 1 km^2 area at Jabiluka was 1380 mm. Jones et al (1999) cautioned that the estimated probable maximum precipitation of Bureau of Meteorology (1999) may have been underestimated by up to 35% for durations greater than 2 hours and for areas of 50 to 70 km^2. Clearly, ERARM and Magela Creek have only experienced relatively small events in comparison to maximum recorded daily rainfall and the probable maximum precipitation since mining began.

As noted by Riley and East (1990, 7),

> It is highly likely that during the expected structural life of the structure, events will occur with recurrence intervals of the order of 1000 years, approaching probable maximum values of rainfall and runoff.

The structure referred to is the ERARM rehabilitated mine site. Clearly it is essential that the estimates of maximum rainfall and floods are as reliable as possible to ensure that all artificial landforms can withstand the resultant erosional forces. If they cannot, very high erosion rates will occur that could breach the cap material used for mine rehabilitation. The rainfall time series used in the SIBERIA landform evolution modelling does not include any extreme events because it is based solely on the short Jabiru rainfall record (Willgoose & Riley 1993, 1994, 1998). Therefore, vastly different results may be documented with a more representative rainfall time series.

6.2 Extreme floods

Little is currently known of extreme flood events on Magela Creek and its tributaries. According to Roberts (1991), the maximum flood recorded at gauge 8210009 had a peak discharge of 1580 m^3s^{-1}, which is only 3.51 times greater than the mean annual flood (herein called the *flood peak ratio*). Roberts (1991) also cited a probable maximum flood of 6150 m^3/s, which has a flood peak ratio of 13.7. Floods at least 10 times greater than the mean annual flood have totally destroyed many sand-bed channels and sandy floodplains in Australia (Erskine 1993, 1994a, 1996a, 1999, Erskine & White 1996, Erskine & Saynor 1996b, Erskine & Livingstone 1999). Erskine (1994a) reported floods with peak discharges up to 43.4 times the mean annual flood and Erskine and Saynor (1996b) reported floods with peaks up to 45.0 times the mean in southeastern Australia. While flood variability is less in the seasonally wet tropics than further south, catastrophic floods still occur and will cause major channel and floodplain erosion (Erskine 1993, 1994a, 1996a, 1999, Erskine & Saynor 1996a,b).

Pickup et al (1983, 1987) emphasised that rare catastrophic floods cause large amounts of erosion over a very short-time period and that it is, therefore, necessary to obtain information on the probability and magnitude of catastrophic floods in the Alligator Rivers Region. In the Northern Territory, rainfall and river gauging records are short and may contain outliers (Pickup et al 1987). As a result, standard rainfall and flood frequency analyses are unreliable. Palaeoflood hydrology involves the use of geomorphic techniques to greatly extend hydrologic records over thousands of years (Baker 1987, Kochel & Baker 1988, Pickup 1989). This is particularly important when the time spans involved cover the period of the present climatic regime when boundary meteorological conditions are effectively constant (Saynor & Erskine 1993).

The basis of palaeoflood hydrology is the use of various indicators that record the height of large floods that occurred before the start of modern hydrographic measurements. Slackwater deposits in bedrock gorges are usually used as palaeostage indicators (Baker 1987, Pickup 1989, Gillieson et al 1991, Saynor & Erskine 1993). Slackwater deposits (SWDs) are typically fine-grained sand and silt that accumulate rapidly from suspension during extreme floods in protected areas where current velocities are locally reduced (Baker et al 1983). The location of suitable sites in bedrock gorges are well documented as including:

1. Shallow caves along the bedrock walls of a gorge;
2. Tributary mouths;
3. Flow separation envelopes with reverse (ie upstream directed) currents in expanded areas or downstream of major obstructions; and
4. Overbank deposits on high river terraces or bedrock benches (Kochel & Baker 1988, Pickup et al 1988).

SWDs record the minimum peak height of a flood because there must be water above the surface of the SWD to produce deposition (Baker 1987). Multiple sites in a gorge should be investigated to obtain a meaningful long profile of the formative events. However, SWDs must be unambiguously differentiated from surrounding unconsolidated sediments and this may necessitate detailed mineralogical analyses to discriminate between local and distant sediment sources (Saynor & Erskine 1993). Once the peak stage profile of a palaeoflood has been established for a reach of channel, the corresponding peak discharge is estimated by an energy balanced backwater flow model based on channel cross sections and roughness coefficients (Baker 1987, Baker & Pickup 1987, Pickup 1989). These sections must *not* change in dimensions over time to estimate reliable discharges. For this reason, resistant bedrock gorges are used for time spans of 10^3 years. Furthermore, deep, narrow bedrock gorges produce measurable stage changes with increasing peak discharge. Sandstone gorges of the Kombolgie Formation are excellent for palaeoflood analyses (Baker & Pickup 1987, Wohl 1988, Wohl et al 1994a). Palaeoflood data can also be used to check the magnitude of the probable maximum flood (PMF), as was undertaken for Warragamba Dam when estimates of probable maximum precipitation (PMP) were greatly increased (Saynor & Erskine 1993). This is important work because probable maximum flood is being used increasingly for engineering design (Gillieson et al 1991). SWDs were employed to reconstruct the peak flows of the largest known terrestrial discharges, the late Pleistocene ice-dammed lake failures in the Altay Mountains of south-central Siberia (>18 × 10^6 m^3/s, Baker et al 1993) and the maximum late Pleistocene glacial Lake Missoula flood discharges (>17 × 10^6 m^3/s, O'Connor & Baker 1992).

Pickup et al (1983, 1987) recommended investigations of slackwater deposits and palaeofloods on the Katherine River in the Katherine Gorge, East Alligator River in the sandstone gorge upstream of Cahills Crossing and Magela Creek upstream of Bowerbird Waterhole. The Katherine Gorge work was completed by Baker et al (1985, 1987) and Baker and Pickup (1987). They found that the then largest historical flood of March 1957 had a peak discharge of at least 5000 m^3/s but that a larger undated flood with a peak discharge of at least 6300 m^3/s had also occurred in the recent past. This palaeoflood has been dated at 440 ± 60 BP (Wohl et al 1994a). The January 1998 flood had a peak discharge of 12 000 m^3/s at Katherine. Baker and Pickup (1987) convincingly demonstrated that the morphology of this bedrock channel was formed by these large floods which generated mean flow velocities of 7.5 m/s, flow depths of 15–45 m, a mean stream power of 10 000 W/m^2 and bed shear stresses of 1500 N/m^2. Such catastrophic floods transported boulders with diameters of 3 m or more, scoured pools at vertical joint intersections, and formed potholes, flutes, abraded facets and channelled scabland in bedrock.

Pickup et al (1987, figs 10–14) mapped in detail the surficial sediments on the lower 40 km of gorge on the East Alligator River. They identified two high level SWDs and recommended that detailed work be completed in this area. Wohl (1988) and Wohl et al (1994a) investigated these sites and Murray et al (1992) reported thermoluminescence, radiocarbon and excess ^{226}Ra decay dating of the SWDs. Wohl et al (1994a) concluded that thermoluminescence dating may not be applicable to dating SWDs because of incomplete bleaching during transport by floods. Wohl (1988) also noted that these sites were far from ideal for palaeoflood hydrology because of the potential for scour and fill of the sand bed. The reconstructed peak discharges were relatively small, having been exceeded during the 15 years of gauging data (Wohl 1988, Wohl et al 1994a). Therefore, the sites investigated to date on the East Alligator River have *not* yielded worthwhile data on the peak discharges of palaeofloods.

Although the sandstone gorge on upper Magela Creek was also recommended for investigation (Pickup et al 1987), this work has not been undertaken. From the information contained in the Environmental Research Institute of the Supervising Scientist file 'JR/04/53 – Slackwater Deposits/Palaeohydrology Research in East Alligator Region', it is apparent that Ellen Wohl was expected to complete this work while at the Institute as part of her visit to the Alligator Rivers Region. However, the lack of carbonaceous material in the East Alligator River SWDs led to Wohl's pioneering but time consuming work on the thermoluminescence dating of SWDs (Murray et al 1992, Wohl et al 1994a). As a result, no investigations of the SWDs in the sandstone gorge of Magela Creek have been completed (E Wohl 1997, pers comm).

Aerial inspections of the Alligator Rivers Region for this project (Saynor & Erskine 1998) found better sites for SWDs on the East Alligator River upstream of the area mapped by

Pickup et al (1983, 1987) and investigated by Wohl (1988, Wohl et al 1994a, Murray et al 1992). Further upstream is a true bedrock gorge that contains high level SWDs (Saynor & Erskine 1998). This reach is suitable for the reconstruction of palaeoflood discharges because the channel boundary is cut entirely in resistant bedrock, unlike the sites investigated by Murray et al (1992) and Wohl et al (1994a).

Palaeoflood peak discharges reconstructed from SWDs elsewhere in the seasonally wet tropics of Australia have often greatly exceeded maximum recorded flows. Gillieson et al (1991) found that the largest palaeoflood (ie highest SWD) in Windjana Gorge on the Lennard River in the Kimberley Region of Western Australia exceeded the maximum gauged flood. Wohl et al (1994b) reported peak discharges for palaeofloods reconstructed from SWDs on the nearby Fitzroy and Margaret Rivers in the Kimberley Region of Western Australia that were substantially higher than those from the gauged record. In fact, the palaeofloods plotted on the upper limit of reported maximum rainfall-runoff floods for northern Australia. All of these events occurred in the last 4 ka.

Nott (1996, Nott et al 1996) maintained that SWDs did *not* record extreme floods in tropical Australia and that his work on alluvial levees was more appropriate for the reconstruction of palaeofloods. Nott and Price (1994) used beach ridges (*sic*) at the downstream margin of the Gunlom plunge pool on Waterfall Creek in the South Alligator River catchment to reconstruct palaeoprecipitation trends. They argued that plunge pool expansion and ridge construction occurred during wet phases with higher discharges at about 22–20 ka and 8–5 ka (Nott 1996). However, Nott et al (1996) not only reinterpreted the beach ridges as levees but also related their formation to large floods instead of periods of increased runoff. Nott (1996) did not consider that there could be incomplete bleaching of quartz sand grains during transport by floods and hence thermoluminscence dates of quartz sand flood deposits may be unreliable (Wohl et al 1994a). Clusters of large floods occurred between 30 and 20 ka and between 11 and 4 ka at both Gunlom and Wangi Falls. Nott (1996) cited these clusters as occurring between 22–20 ka and 8–5 ka at Gunlom Falls and between 30–22 ka and 8–4 ka at Wangi Falls. All of the large floods recorded by Wohl et al (1994b) in the Kimberley Region occurred during the last 4 ka. Nott (1996) and Nott et al (1996) estimated peak discharges for the floods, which formed the levees as essentially equalling the largest floods ever recorded in the world for comparable catchment areas. However, they did not provide details of the hydraulics of their method of discharge estimation. Furthermore, they considered an alluvial channel boundary of unknown dimensions at the time of these floods and hence peak discharges *cannot* be reliably estimated (Baker 1987, Kochel & Baker 1988, Pickup 1989). Wasson et al (1998) placed unwarranted confidence in Nott's (1996) work. Nevertheless, Nott (1996, Nott et al 1996) argued that flood time series were non-stationary over time periods of 10^3 years, a point more convincingly demonstrated over time periods of $>10^1$ years by Erskine (1986, Erskine & Bell 1982, Erskine & Warner 1988, 1999).

SWDs in bedrock-confined gorges offer the best potential for reconstructing the peak flow of palaeofloods in the seasonally wet tropics. Further work is needed to establish the magnitude of extreme floods during the late Holocene in the Alligator Rivers region.

6.3 Erosional and depositional effects of extreme floods

Catastrophic floods in south-eastern Australia have been found to generate between at least 11 and 283 times the mean annual sediment yield from channel erosion alone (Erskine & Saynor 1996b). Much of the eroded sediment is temporarily stored in the channel as bedload waves and on the floodplain as extensive sand splays and sheets (Erskine 1993, 1994a, 1996a, Erskine & Saynor 1996b), and is subsequently reworked. In the short term catastrophic floods can generate all of the sediment yield by channel erosion alone (Erskine & Saynor 1996a,b, Erskine 1999). A catastrophic flood has not been recorded since the start of mining on Magela Creek and hence there are no contemporary observations and measurements of flood erosion and flood-induced channel changes. Monitoring of channel conditions on the mine site tributaries and Magela Creek in the sand anastomosing zone would enable the measurement of channel erosion caused by catastrophic floods.

There are at least two avulsions preserved on the East Alligator River floodplain near Cahills Crossing (fig 14). While floods still activate parts of these abandoned channels (Saynor & Erskine 1998) so that they superficially appear to be flood chutes, very long sections are now totally abandoned (fig 14). Bedrock outliers are located between the present channel and the abandoned channels. East et al (1993) also recognised the potential for channel avulsions on the Magela Creek sand zone next to ERARM. Patton et al (1993) found that the surface features of the Ross River floodout near Alice Springs were produced by catastrophic floods.

Figure 14 Avulsions of the East Alligator River on the floodplain at Cahills Crossing

A palaeochannel was also present there as well as low relief bars and low relief long wavelength bedforms. These landforms and deposits were produced by a flood flow up to 10 km wide that inundated the whole plain. The topographic setting of the Ross River floodout is similar to the East Alligator River at Cahills Crossing and Magela Creek downstream of Bowerbird Gauge. No assessment of the potential for, and causes of, channel avulsions and their significance for erosion of the rehabilitated mine site on the Koolpinyah Surface next to Magela Creek has been conducted. The work completed to date has been concerned with Quaternary landform evolution and the stability of these landforms for the long-term containment of mine waste (Nanson et al 1990, 1993, Roberts 1991, East et al 1993). The best site on Magela Creek for investigating the role of catastrophic floods in alluvial landform development is immediately downstream of the bedrock gorge, which terminates at the Bowerbird Gauge.

7 Long-term behaviour of Magela Creek and its tributaries

The late Quaternary history of Magela Creek and its tributaries have been investigated in detail by Nanson et al (1990, 1993), East et al (1989b, 1993), Roberts (1991) and Clark et al (1992a,b). This work has reconstructed environmental changes that may be relevant to the prediction of landform response to future climate and sea level changes. In this section, the late Quaternary history of the mine site tributaries, the anastomosing sand zone of Magela Creek and the lower floodplain of Magela Creek are outlined and used to predict channel response to future environmental changes.

7.1 Mine site tributaries

Nanson et al (1990, 1993) found that the mine site tributaries did not erode deeply into their bedrock basement during lower sea levels and joined Magela Creek at waterfalls (see Nanson et al 1993, fig 7). Pleistocene sediments are preserved at depth in both Georgetown and Gulungul Creeks. On Georgetown Creek, there is a complex sequence of stratified sands, mottled clays, sandy clays and basal gravels, filling a shallow bedrock valley. Age reversals were found and indicate that thermoluminescence may not be an appropriate dating technique in small catchments (Nanson et al 1993). On Gulungul Creek, thin gravel and extensive medium to coarse sand filled the bedrock trench to about 79 ka. Then a laterally migrating channel was active between 23 and 12 ka and deposited a sheet of fining upwards clean sand. Probable Holocene sediments form a thin cap on top of the late Pleistocene sand.

7.2 Magela Creek anastomosing sand zone

The generalised chronostratigraphic units of the Magela Creek anastomosing sand zone are shown in figure 15. The valley is slightly incised into the Tertiary Koolpinyah Surface but the bedrock basement is a deep trench cut into Lower Proterozoic metasediments. The alluvial cap on the Magela Ridge is probably of Tertiary age and the deep alluvial fill of the bedrock trench accreted between >300 ka and about 150 ka (Nanson et al 1993). Deposition is still occurring today. During lower sea levels, palaeochannels were incised into these Pleistocene deposits and subsequently backfilled. Palaeochannel 1 is the anastomosing sand-bed channel discussed in section 5.

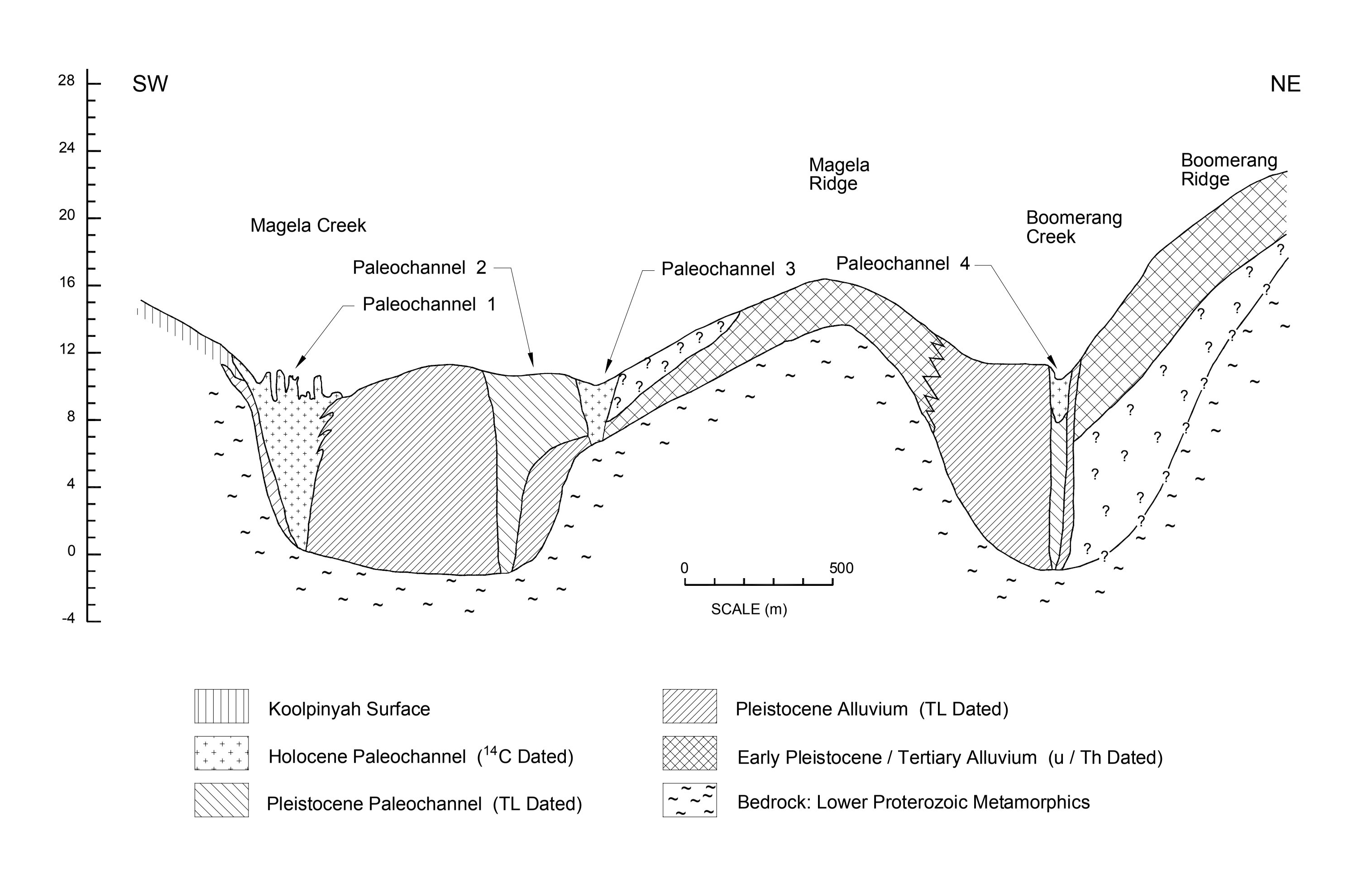

Figure 15 Generalised chronostratigraphic units of the Magela Creek valley-fill next to ERARM (East et al 1993)

7.3 Lower Magela Creek floodplain

Clark et al (1992a) identified five major stratigraphic units overlying bedrock on the lower Magela floodplain (fig 16). In vertical sequence, these were:

1. Basal fluviatile sands and gravels;
2. A complex body of freshwater interbedded sandy clay, clayey sand, sand and gravelly clayey sand capped by a discontinuous palaeosol;
3. Early- to mid-Holocene estuarine blue grey clay containing a number of clay, peat and sandier lithofacies, which are rich in mangrove pollen and sedimentary pyrite;
4. Late Holocene mottled, oxidised, estuarine grey clay; and
5. Late Holocene dark, organic-enriched, freshwater clays.

East et al (1989b) and Clark et al (1992b) reconstructed the major sedimentary environments corresponding to these stratigraphic units (fig 17). After about 8 ka, sea level rose from about -13 m AHD to near present sea level between 5.5 and 7.0 ka (Woodroffe et al 1987, Clark et al 1992b). This resulted in both the sea flooding the lower Magela valley and the first appearance of mangroves at about 6.2 ka (Clark et al 1992b). Rapid estuarine sedimentation occurred in a *Rhizophora* forest, called the 'big swamp' phase on the neighbouring South Alligator River by Woodroffe et al (1986, 1989). The mangroves retreated downstream from the Mudginberri Corridor to the Central High between 4.4 ka and 2.3 ka. As the strength of tidal connection was progressively severed, transition sediments were deposited and the former tidal channels were dismembered (Clark et al 1992b), forming the channel and floodplain billabongs of Hart and McGregor (1980) and Walker and Tyler (1984). Between about 1.5 and 1.0 ka, freshwater wetlands formed and dark clay or black soil was deposited over the bulk of the lower floodplain (Clark & Guppy 1988, Clark et al 1992b).

7.4 Response to future environmental changes

McQuade et al (1996) pointed out that climate variability is likely to mask for decades any evidence of the climate change suggested by global climate models. Nevertheless, Wasson (1992), Mitchell et al (1994) and Suppiah et al (1998) have predicted future climate change projections in the Northern Territory due to the enhanced greenhouse effect. Bayliss et al (1997) and Eliot et al (1999) used the estimates of Mitchell et al (1994) for the year 2030 for their vulnerability assessment of predicted climate change and sea level rise in the Alligator Rivers Region and summarised the major local predicted climate change as comprising, among other things:

- 1–2°C increase in temperature
- 0–10% increase in total cloud cover
- more intense monsoon
- general increase in rainfall intensities
- possible marked increase in heavy rain events
- more floods and dry spells
- topographic effects (such as the Arnhem Land escarpment) could locally cause two to three times greater change in rainfall
- increase in potential evaporation of 5–15%
- stronger monsoon westerlies and stronger winds during severe weather
- rise in sea level by between 80 and 300 mm.

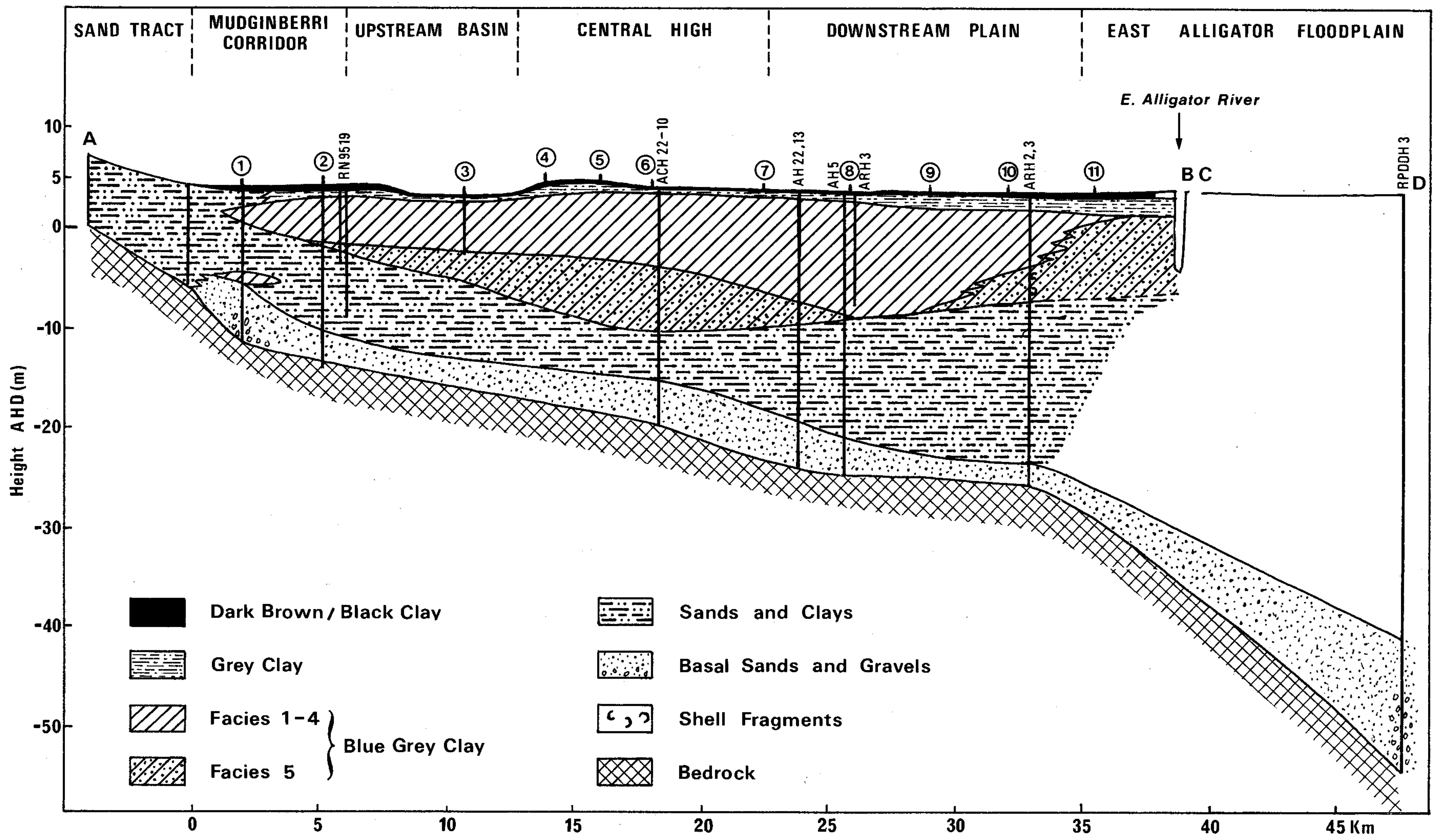

Figure 16 Longitudinal stratigraphy of the lower Magela floodplain, showing the five stratigraphic units of Clark et al (1992a)

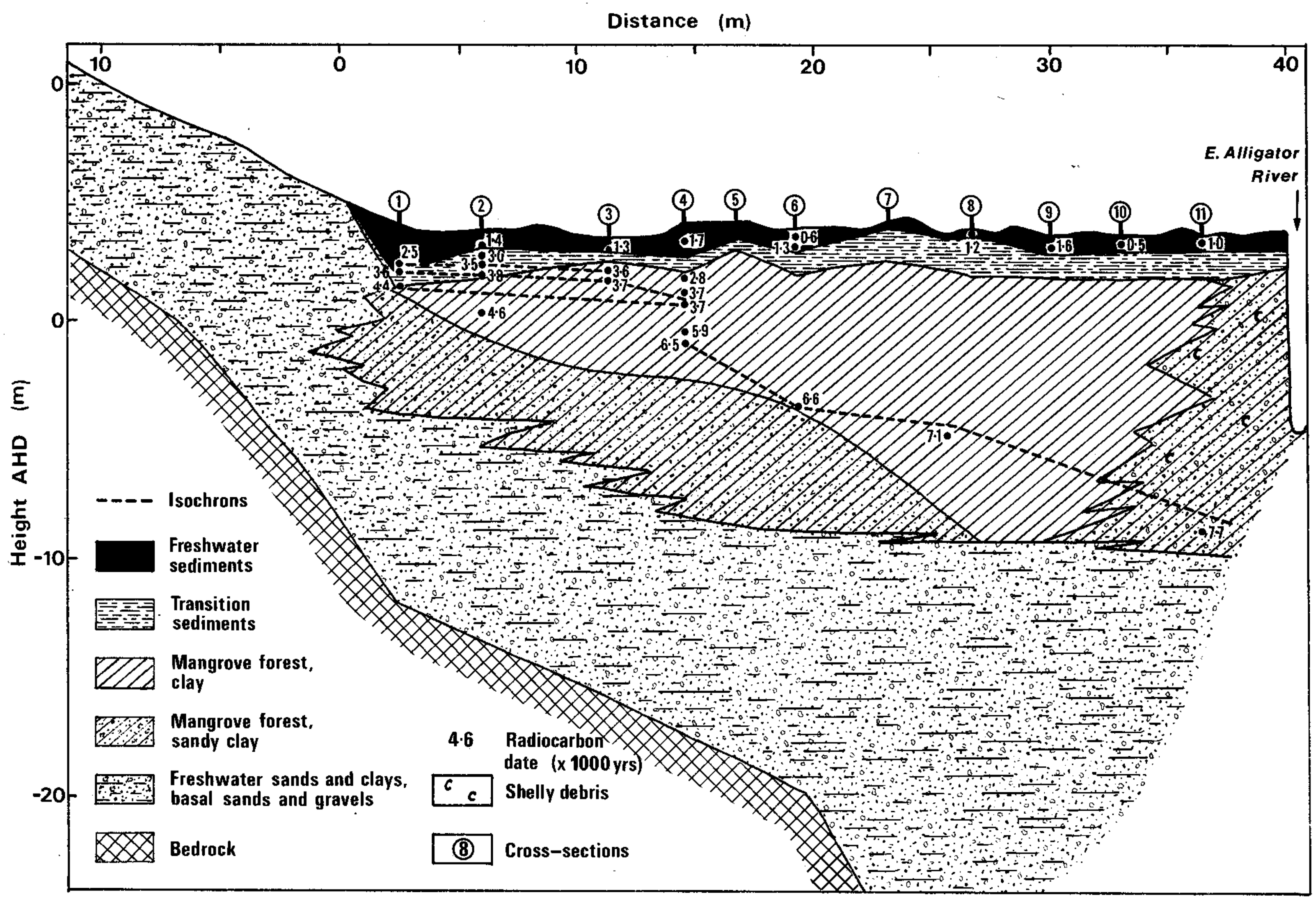

Figure 17 Longitudinal distribution of sedimentary environments of the lower Magela floodplain (Clark et al 1992b)

Jones et al (1999) used the latest general circulation and limited area models combined with a 4% historical increase in rainfall at Oenpelli to estimate the temperature and rainfall at Jabiluka for 2030. Local temperature will increase by only 0.85 to 1.0°C, Wet season rainfall will change by between -6 and +4% and Dry season rainfall will change by between -50 and +6%. Nevertheless, an increase in rainfall is still possible (Jones et al 1999). The regional climate model indicated that there would be little change in mean annual rainfall at Jabiluka by the year 2030 but that extreme rainfall and storm activity would increase substantially (Jones et al 1999). The current 1-in-10 year event becomes a 1-in-7 year event in 2030 (Jones et al 1999). Clearly, these changes are less than those cited above.

Environmental responses to the above greenhouse-induced climate and sea level changes are manifested through hydrological, hydrodynamic, geomorphological and ecological processes that interact with each other (Bayliss et al 1997). The following predictions are often based on a lack of local data and consequently are speculative. They are made in the hope of stimulating future work to address current deficiencies. An increase in storminess due to greater rainfall intensities, more heavy rain events and/or local topographic effects on rainfall will cause higher soil and channel erosion rates. These, in turn, will increase suspended load and bedload, and hence sediment yields. However, the establishment of a dense vegetative cover during the Wet season can significantly reduce soil erosion rates (Saynor & Evans 2000). Changes in Wet season rainfall reliability will interact with vegetative cover to influence soil erosion rates. Furthermore, the widespread use of fire during the Dry season also interacts with rainfall during the next Wet season to cause higher soil erosion rates (Evans et al 1999). Repetitive intense late Dry season burns of rehabilitated mine sites and Wet season runoff producing (ie saturated) zones should be discontinued in the future, to prevent further increases in soil erosion rates. Monsoon forests and riparian vegetation are important stabilising factors on sand bed streams in the Alligator Rivers Region (Nanson et al 1993). Such vegetation should not be burnt at any time so that it can continue to protect sand bed streams from the erosive forces of large floods. Similarly large woody debris in these river channels must be maintained to provide large scale roughness elements which serve to reduce in-channel flow velocities. The predicted higher soil erosion rates and sediment yields will also occur on the rehabilitated mine site. Downstream sediment storages will also be reworked. This will cause higher wetland (backflow and channel billabongs) sedimentation rates.

A sufficiently large rise in sea level due to global warming will re-establish tidal connection with the former tidal channels of the Downstream Plain and possibly the Central High on lower Magela Creek (Wasson 1992). The simple reversal of the late Holocene environmental changes (ie freshwater to transition to mangrove forest) is not the inevitable trend (Wasson 1992) because the rate of rise is predicted to be much slower than for the Holocene marine transgression. Transition conditions are more likely and salinisation of extensive areas of freshwater wetlands can be expected (Bayliss et al 1997, Eliot et al 1999), as documented recently on the nearby Mary River (Mulrennan & Woodroffe 1998). However, hydrodynamic effects on tidal behaviour due to sea level rise are likely to vary across rivers because of differences in tidal channel geometry. Furthermore, variations in tidal range (ie low and high tide levels) will be just as important as changes in mean tide levels. Sea level rise is unlikely to impact on Magela Creek next to ERARM. However, the associated increased rainfall (Wasson 1992) or increased storminess (Jones et al 1999) will increase discharge and sand transport. This should cause bed aggradation, accelerated sand deposition on the floodplain and further damming of the mine site tributaries at their junction with Magela Creek (ie enlarged backflow billabongs with higher sediment trap efficiencies). Greater sand storage of sediment generated on the mine site would also occur in the anastomosed sand zone. However, current estimates of sea level rise by 2030 (see above) are at the lower end of the values discussed by Wasson (1992). Therefore, the immediate effects of sea level rise are likely to be small in magnitude.

A fall in sea level is predicted within the next 5 ka as the next glacial starts (Wasson 1992). It will cause incision of the freshwater, transition and estuarine sediments of the lower Magela floodplain and the sand fill of the current anastomosing sand-bed channel on the western side of the valley near ERARM. This will, in turn, rejuvenate the mine site tributaries and erode the backflow billabongs. The tributaries will become fully integrated with the main stream and supply more sediment than is currently the case. Clearly, any mine-site generated sediment would be extensively reworked out of the mine site tributaries as a result of a substantial fall in sea level. Oxidation of the lower Magela estuarine sediments will generate acid and high iron contents by the oxidation of pyrite and organic matter. If tailings were stored with these sediments, heavy metals would also be mobilised.

8 Conclusions

As outlined in section 1, the purpose of this report was threefold:

1. To collate and review all of the existing data relevant to the discharge of solutes and particulate material from the rehabilitated mine site and from nearby tributaries of Magela Creek;
2. To determine the fate of particulates in the off-site system; and
3. To collate and review all of the existing material relevant to an understanding of the long-term behaviour of Magela Creek and its tributaries.

Although natural solute and sediment yields in the Alligator Rivers Region are low by world standards, mine sites can produce significantly higher yields. Disturbed sites generate sediment yields that are an order of magnitude higher than those from natural catchments. Large storms dominate soil erosion and sediment transport in the Alligator Rivers Region. Up to 7 m of erosion and 20.4×10^6 t of sediment will be eroded from the rehabilitated mine site over the 1000 years structural life. Assuming sediment delivery ratios of between 0.24 and 0.50, up to 15.5×10^6 t will be stored on site and up to 10.2×10^6 t will be transported off the mine site (table 5). Vegetation, the installation of convexo-concave slope profiles and the use of surficial gravel lags will all reduce the soil erosion rate on the rehabilitated mine site and should be incorporated in the final rehabilitated mine design.

The mine site tributaries and the backflow billabongs will be the most significant sediment storage sites downstream of the mine site. The backflow billabongs will be completely infilled with mine-derived sediment over the 1000 years structural life of ERARM rehabilitated mine site. Relatively little sediment storage will occur in the anastomosing sand zone of Magela Creek but the lower floodplain will trap and store essentially all of the mine-derived sediment supplied to it, if sufficient sediment is generated from the rehabilitated mine site.

Sea level rise will re-establish tidal connection with the old tidal channels and cause extensive salinisation of the most downstream wetlands on Magela Creek. This will cause the remobilisation of stored sediments but a large proportion should be redeposited elsewhere on the floodplain.

A substantial fall in sea level will result in incision of Magela Creek downstream of ERARM and the remobilisation of massive amounts of stored sediments and the oxidisation of the remaining sediments. Mine site tributaries will be rejuvenated and any mine site generated sediment will be flushed into Magela Creek.

While a disproportionately large effort has been directed at understanding the evolution and behaviour of the sand anastomosing reach and lower floodplain of Magela Creek, these sections will not be the initial repositories for mine-derived sediment. The mine site tributaries are not as well understood but are certainly more important sediment stores and sediment pathways. The reason for this discrepancy in research effort is that the lower Magela wetlands are internationally significant and have, therefore, been perceived as being the most important ecosystem likely to be impacted by mining. Under the most likely post-rehabilitation scenario (scenario 4 in table 5) no mine site generated particulates will reach the lower Magela wetlands.

9 Recommendations

The above review has highlighted the following two areas where additional research is essential to improve the assessment and prediction of the off-site geomorphic impacts of uranium mining on Magela Creek. Each of these additional research projects is briefly outlined below.

9.1 Mine site tributaries

Little is currently known of channel stability, the probability of gullying, and sediment movement and storage, on the mine site tributaries, particularly Gulungul Creek. The work of Nanson et al (1993) and East et al (1993) does not address the issue of their contemporary activity only their Quaternary evolution and geological stability. Cull et al (1992) applied regional relationships to estimate their sediment budget. These tributaries will be the first to receive sediment generated from the rehabilitated mine site and should store large amounts of the supplied sediment for a relatively long period of time. Therefore, they should be investigated to the extent recommended by Pickup et al (1983, 1987). A geomorphic and hydrologic monitoring program should be implemented. Monitoring should include discharge, sediment transport and water quality at gauging stations located upstream *and* downstream of the mine site. In addition, geomorphic characterisation of the channel and floodplain in homogeneous reaches, the installation and periodic resurvey of permanently marked channel and floodplain cross sections, characterisation of channel and floodplain sediments, and the seasonal and inter-annular variation in the geomorphic, hydrologic and limnological behaviour of the backflow billabongs should be assessed. Datalogging of selected water quality parameters (pH, electrical conductivity, dissolved oxygen, redox potential, temperature, turbidity) at least near the surface and near the bottom of Gulungul and Georgetown Billabongs should be carried out over at least daily periods each month to assess whether thermal and oxygen stratification develop and persist. Furthermore, the same datalogging of water quality parameters must be carried out over a longer time period during the first flush of the Wet season to understand the development of acid stratification documented by Hart and McGregor (1980). Historical channel changes based on the complete coverage of vertical air photographs should also be determined to identify sites of stability, erosion and deposition. The probability of gully initiation on unchannelled reaches and the sediment yields produced by such gullying also require quantification.

9.2 Extreme events

It is essential that the probability and magnitude of extreme storms and floods are more accurately defined because of their potential significance for soil erosion, sediment transport, channel changes and avulsions, and landform evolution modeling by SIBERIA. This can be achieved by extending the only previous palaeoflood analyses on the Katherine Gorge by Baker and Pickup (1987). The Australia Day flood of 1998 on the Katherine River provides a rare opportunity to carry out detailed investigations of contemporary SWDs, to check the accuracy of the discharges reconstructed by the SWD technique and to determine appropriate correction factors. Peter Sandercock may have already undertaken this work as part of his honours thesis at the Department of Geography, University of Western Australia. To date, we have not been able to view a copy of his thesis.

Preliminary aerial reconnaissance of the East Alligator River upstream of the area mapped in detail by Pickup et al (1983, 1987) and investigated by Murray et al (1992) and Wohl (1988, Wohl et al 1994a), for this project revealed better sites and higher level SWDs than those previously investigated (Saynor & Erskine 1998). These sites should be analysed for their SWDs and palaeoflood record. Furthermore, the investigations of Magela Creek recommended by Pickup et al (1983, 1987) have still not been undertaken (E Wohl 1997, pers comm). This work should also be completed, particularly as aerial inspections for this project revealed that the gorge below Magela Falls is an excellent site for the preservation and analysis of SWDs. The role of catastrophic floods in causing the two avulsions on the East Alligator River floodplain at Cahills Crossing needs to be determined to assess the potential for avulsions on Magela Creek next to ERARM. The model of channel avulsions on floodplains in south-eastern Australia proposed by Erskine et al (1990) and Schumm et al (1996) should be evaluated for its relevance to rivers in the seasonally wet tropics. While Nanson et al (1990, 1993) did not record any Holocene avulsions on the anastomosing sand section of Magela Creek next to ERARM, this does not mean that avulsions will not occur as the anastomosing channels continue to aggrade, as predicted by Nanson et al (1993). Late Holocene avulsions of Magela Creek may have occurred immediately downstream of the upper bedrock gorge. It is *recommended* that the following three projects should be undertaken:

1. Assessment of the contemporary SWDs laid down by the January 1998 flood in the Katherine Gorge and their reliability for estimating the peak flood discharge of the formative flood. This work may have already been completed by Peter Sandercock;
2. Detailed analyses of the SWDs and palaeofloods in the true sandstone gorges on the East Alligator River upstream of the area mapped by Pickup et al (1983, 1987) and on Magela Creek between Magela Falls and Bowerbird Waterhole to determine whether any catastrophic floods have occurred in the Alligator Rivers Region during the mid- to late-Holocene; and
3. Determination of the cause of Holocene avulsions on the East Alligator River at Cahills Crossing so as to assess the sensitivity of Magela Creek near ERARM to future avulsions. Magela Creek upstream of ERARM should also be covered by the investigation. In particular, the association between avulsions and the palaeofloods identified immediately upstream in the true East Alligator River gorge needs evaluation.

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