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.

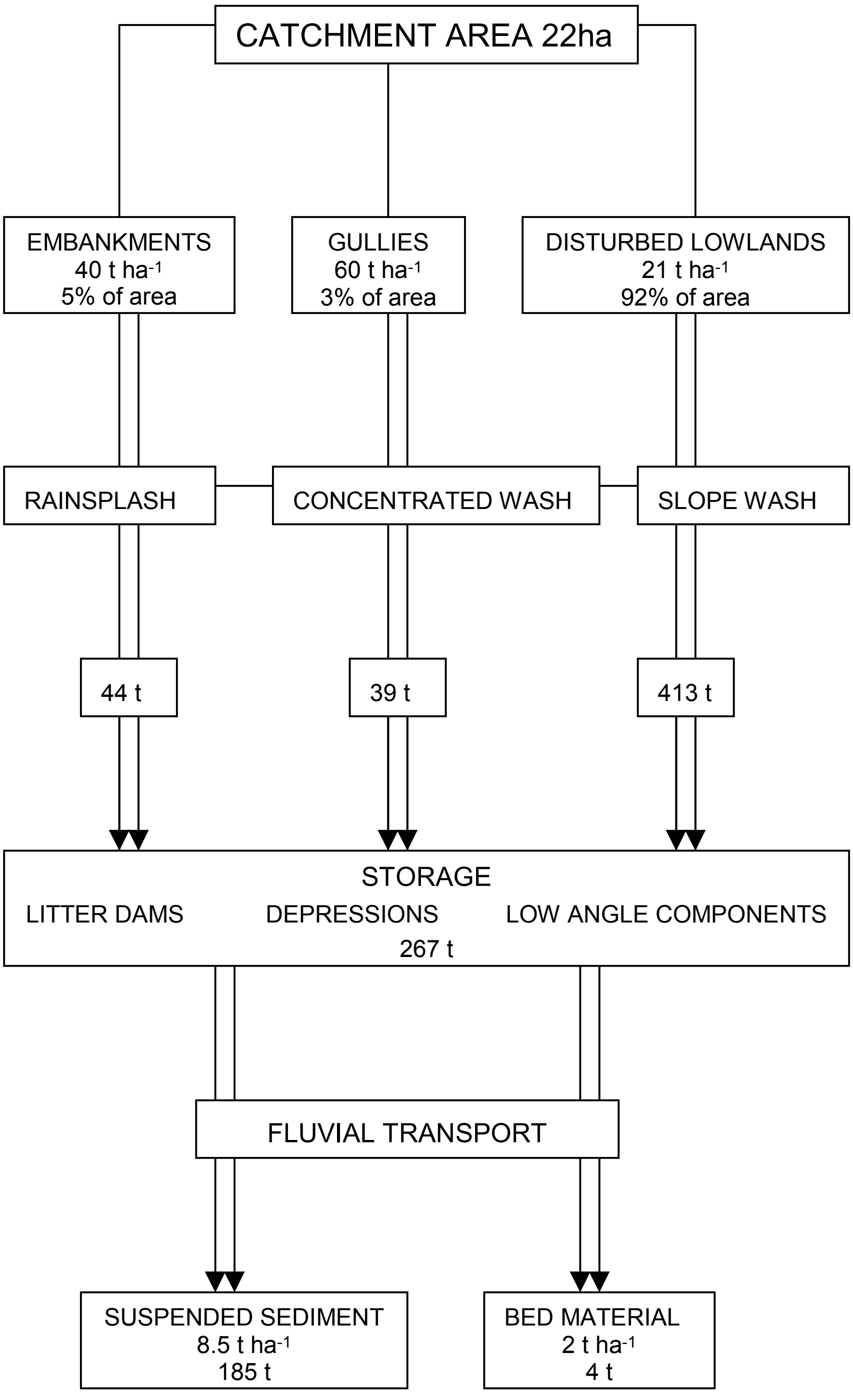

Figure 11 Duggan's (1988) sediment budget for Ranger Tributary for year 2 of measurements

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.

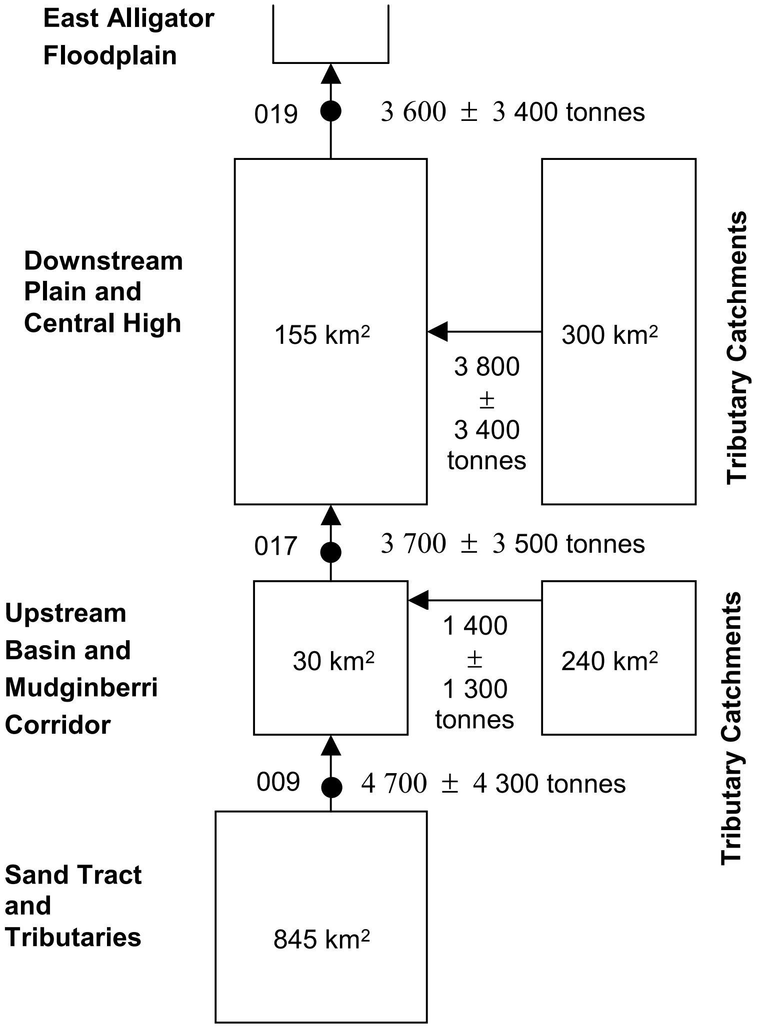

Figure 13 Mean annual fluxes of suspended sediment through the Magela Plain (Cull et al 1992)

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