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 20.4×10^6 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.