Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. no. 224, 1994.

Erosion and sediment yields in the Kakadu region of northern Australia

KATE DUGGAN
Agriculture and Environment Consulting, 72 Ellendon Street, Bungendore, New South Wales 2621, Australia

Abstract The undisturbed landscape of the Kakadu region of northern Australia is highly stable despite it's geographic position in the wet/dry tropics; a world zone which exhibits the highest rates of water erosion and sediment yield. Measured sediment yields in the Australian region are low by world standards and are comparable to the low rates typical of the Australian continent in general. In the Kakadu region, erosive rainfall is countered by erosion resistant landforms; the rocky plateau surfaces and the gravel armoured lowlands. On the lowland slopes, the litter cover formed during the prolonged dry season also plays a role in limiting soil erosion but vegetation cover in general is not as important as the surface lag gravel in limiting erosion. Once the lag is disturbed, erosion rates increase by 2 orders of magnitude and rapid gully erosion occurs even on very gentle slopes. The lag can be encouraged to reform on disturbed lowland slopes through reformation of the former contours and use of local, gravely topsoil. Rehabilitation programmes based on this approach are likely to be more efficient and persistent than the Australian standard methods involving initial establishment of a dense exotic vegetation cover.

INTRODUCTION

The Kakadu region of Australia is part of an extremely old landscape in an ancient continent. In this landscape, weathering and erosion over many millennia have produced intricate rocky escarpments and vast lowland plains. It is an outwardly stable landscape in which landforming processes, although many and varied, are generally slow and insidious.

If the Kakadu region is unspectacular in any respect it is in relation to this geomorphological activity. In the undisturbed environment, processes such as soil erosion and sediment transport are active but very weak. The most spectacular landforming events are perhaps the isolated rock falls from scarp surfaces.

The stability of the Kakadu landscape is unusual considering its position within the wet/dry tropics. In this zone, the annual coincidence of drought ravaged vegetation cover following the prolonged dry season, with the onset of intense wet season rains, produces amongst the world's highest natural rates of soil erosion.

This paper examines why the landscape of Kakadu is so stable and why it is nonetheless highly susceptible to development pressures. It also proposes that conventional soil conservation techniques will not necessarily assist in stabilizing land used intensively in this region. It is argued that the development of land management practices which *are* suited to the Kakadu region depends on an understanding of how these practices interact with natural land forming processes.

This paper draws from a large body of soil erosion and sediment transport data collected between 1979 and 1987 in both disturbed and relatively pristine drainage basins. These data relate primarily to the impacts of land clearing associated with mining, but also generally apply to any intensive land use involving clearance of vegetation on the lowlands.

THE KAKADU ENVIRONMENT

The Kakadu region encompasses an area of over 20 000 km^2 in the northwest of Australia's Northern Territory. The region includes the basins of the East, South and West Alligator Rivers. The rivers rise in the rocky Arnhem Land Plateau in the east and flow across gently sloping, wooded lowlands and flood plains to the Arafura sea. The region includes Kakadu National Park, Australia's first proclaimed World Heritage area. It also contains abundant mineral deposits, notably gold and uranium, and a uranium mine (Ranger Uranium Mine) currently operates in the drainage basin of the East Alligator River. This mine is serviced by a settlement of around 1500 people at Jabiru.

Landforms

The major landforms of the Kakadu region are:

(a) The sandstone plateau, scarps and rocky outcrops of the geological formation known as the Kombolgie Formation. Kombolgie sandstone, composed of quartz sandstone with minor conglomerate and interbedded volcanics (Needham *et al.*, 1980), is unconformable on the Lower Proterozoic metasediments and gneissic equivalents of the Pine Creek Geosyncline (Stuart-Smith *et al.*, 1980). The Kombolgie Formation covers much of the area in the south-east of the region, forming the Arnhem Land Plateau, but has been substantially removed through dissection and scarp collapse in the north and west (Galloway, 1976). The Plateau is inclined gently eastwards but forms an abrupt scarp along the western margin, rising to 300 m above the lowlands.

(b) The gently sloping, wooded lowlands. The lowlands comprise a level to undulating, weathered terrain, supporting open forest and woodland and formed by erosion and duricrusting of the Lower Proterozoic metasediments during the Late Tertiary and early Pleistocene (Williams, 1969). The Lower Proterozoic rocks are irregularly but extensively weathered (Needham, 1972) and are capped by a ferricrete horizon which forms the base of the contemporary soil (Milnes *et al.*, 1986). Dominant soil types are single grained to massive, sandy to gravelly red and yellow earths, earthy sands and siliceous sands. A striking feature of the lowland surface is the presence of a dense gravel lag, comprising vein quartz and ferruginous gravel, forming up to 100% cover on the surface of the dominant red and yellow earths.

(c) The seasonally inundated river systems and flood plains. In the upper reaches and over the lowlands, the river systems are typically anastomosing, sandy channels fringed by woodland vegetation. These channels cease to flow during the dry season and contract to a series of semi-permanent waterholes. In the lower reaches, the wet season floods flow over extensive freshwater flood plains into large, muddy, meandering tidal channels cut into estuarine mangrove swamps. The present flood plains were formed through deposition of about 6 m of estuarine sediments during the last marine transgression (around 10 000 years ago). These are overlain by a more recent layer of fluvial muds (Woodroffe *et al.*, 1985).

Climate

The climate of the region will be dealt with in this paper in-so-far as it influences contemporary erosion and sediment transport. The two most important climatic features in this regard are the prolonged annual drought, broken by an intense wet season, and the high intensity of rainfall events. The annual drought results in a dramatic reduction in vegetation cover, leaving the soil surface exposed to wet season rains, while the high intensity of many of these rains further increases the potential erosion hazard.

The climate is characterized by a hot wet season (December-March) and a hot dry season (May-October). April and November are transitional. Temperatures are high throughout the year with mean monthly maxima of 37°C in November and 31.5°C in July (McAlpine, 1976). Mean annual rainfall ranges from over 1500 mm in the north of the region to 1300 mm in the south, and close to 90% falls in the wet season. Rainfall intensities of 100 mm h^{-1} for 10 min periods may be expected annually and cyclones recur on average once or twice per year (Lee & Neal, 1984). Extreme cyclonic rains may account for up to one third of the annual rainfall total in the space of 24 h (Jackson, 1977). At least 25 such events have been recorded in the north-west of Australia since 1915 (McGill, 1983).

The erosivity of rainfall (based on the EI_{30} index derived by Wischmeier *et al.*, 1958) in the region is high compared with the rest of the Australian continent, exceeded only on Cape York Peninsula in tropical Queensland (McFarlane & Clinnick, 1984). Based on these rainfall characteristics, the Kakadu region may be expected to experience higher than average rates of soil erosion by water.

SOIL EROSION AND SEDIMENT TRANSPORT

A study of erosion and sediment transport was carried out in relatively undisturbed drainage basins in the region between 1981 and 1987. The study involved monitoring of hillslope erosion using bounded runoff plots and erosion pins, and measurement of the sediment yields of four basins ranging in area from 5 to 16 km^2. The basins are otherwise similar in morphology, with major land systems, soils and landforms represented (Fig. 1).

Sediment yields

Monitoring of suspended sediment and solutes in the four drainage basins was carried out using automatic flow recorders and flow proportional samplers (ISCOtn). A total of 3698 samples was collected during the study period. This period included a range of rainfall years with one above average year (1984-1985 wet season), two near average

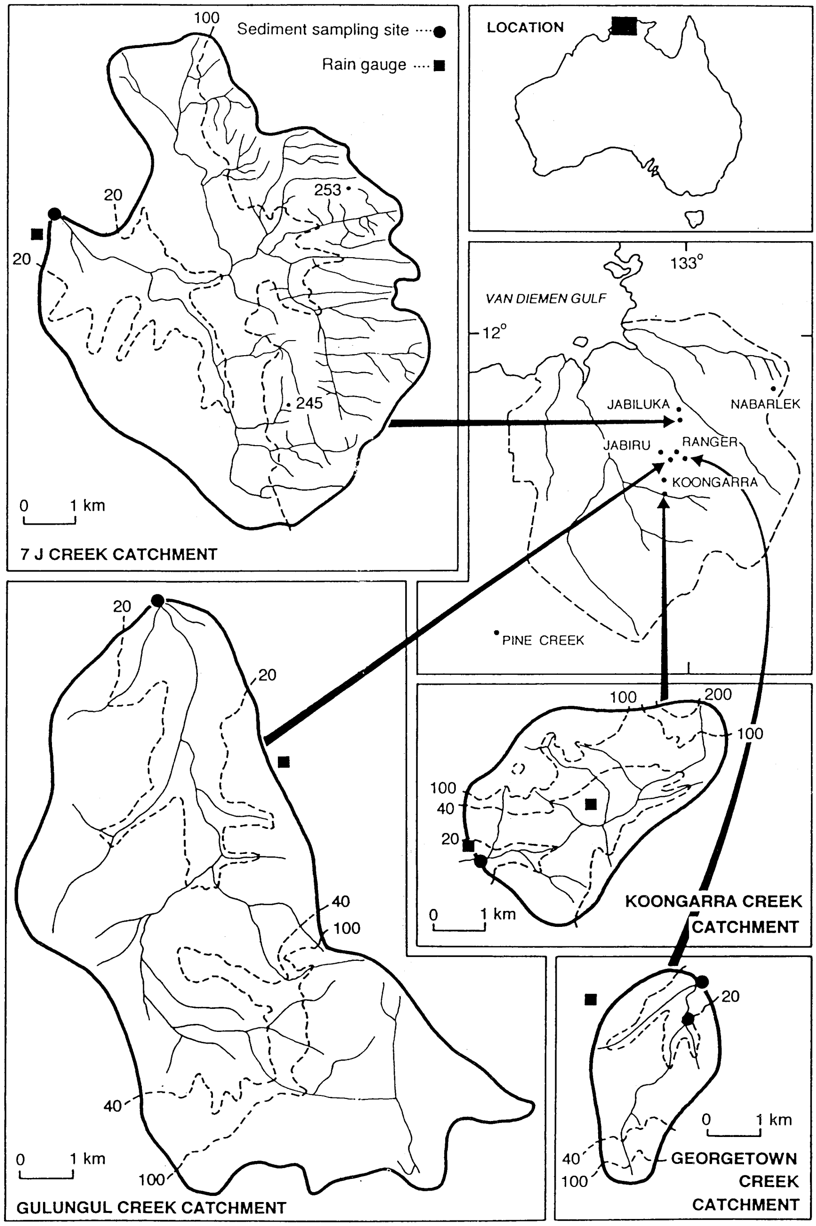

Fig. 1 Map of research basins in the Kakadu region.

years (1981-1983 wet seasons) and two below average years (1985-1987 wet seasons). The high frequency of sediment sampling permitted calculation of actual event yields, integrating sampling intervals of generally less than 1 h and commonly less than 5 min.

The annual suspended sediment and solute yields are shown in Table 1. Mean annual yields of suspended sediment (silt, clay and minor fine sand) and solutes (corrected for atmospheric inputs) for the four basins averaged over nine data years using a specific gravity of 2.5 g cm^{-3}, convert to a mean denudation rate of 12 mm 1000 years^{-1} (SD

Table 1 Sediment yields and rates of erosion and denudation for four drainage basins in the Alligator Rivers region.

Catchment	Area (km^2)	Rainfall (mm)	Discharge (1000 m^3)	Suspended yield (t)	Solute yield (t)	Annual erosion (t km^{-2})	Denudation (mm 100 $years^{-1}$)
Koongarra Creek							
1981-1982	15.4	1452	13 173	489	184	44	17
1982-1983	15.4	1206	8 216	439	126	37	14
7J Creek							
1981-1982	53.5	1451	14 413	505	274	15	6
Gulungal Creek							
1984-1985	61.9	1781	31 109	3607	504	66	26
1985-1986	61.9	967	14 227	697	276	16	6
1989+1987	61.9	1120	19 543	2163	319	40	16
Georgetown Creek 1							
1984-1085	7.8	1781	4 000	250	109	46	18
Georgetown Creek 2							
1985-1986	4.8	967	245	13	5	4	2
1986-1987	4.8	1120	864	47	20	14	6
Mean						31	12

7.8). Volumetric estimates of the bed load component of total sediment yield suggest a long term delivery rate of bed material equivalent to around 4 mm 1000 $years^{-1}$, or around 25% of the total load. The corrected solute yields account for 10 to 25% of the total load, and suspended sediment accounts for around 50 to 65%. Total mean denudation derived from the sum of suspended, solute and bed loads is estimated to be in the order of 16 mm 1000 $years^{-1}$.

Hillslope erosion

Erosion pin experiments in the lowlands over the period 1979 to 1983 provide insight to erosion processes operating on the slopes. A total of 1700 erosion pins were monitored at sites representing the major land systems of the lowlands. At each site, 100 pins (galvanized roofing nails, 10 cm in length) were emplaced flush with the surface at equal intervals along surveyed transect lines (10 m or 20 m) on the contour (a total of 27 transects of 100 pins each). The loss or gain was measured from the head of each pin at the end of the wet season. The values for the 100 pins at each site were averaged to give the mean value of annual surface lowering for the site. The pins were measured once only because of the destructive effect of measuring deposition. The records at each site are therefore for 1 year.

The variation in soil movement across the slope is illustrated for two transect sites (one burnt in the previous dry season) in Fig. 2. This illustration indicates that both

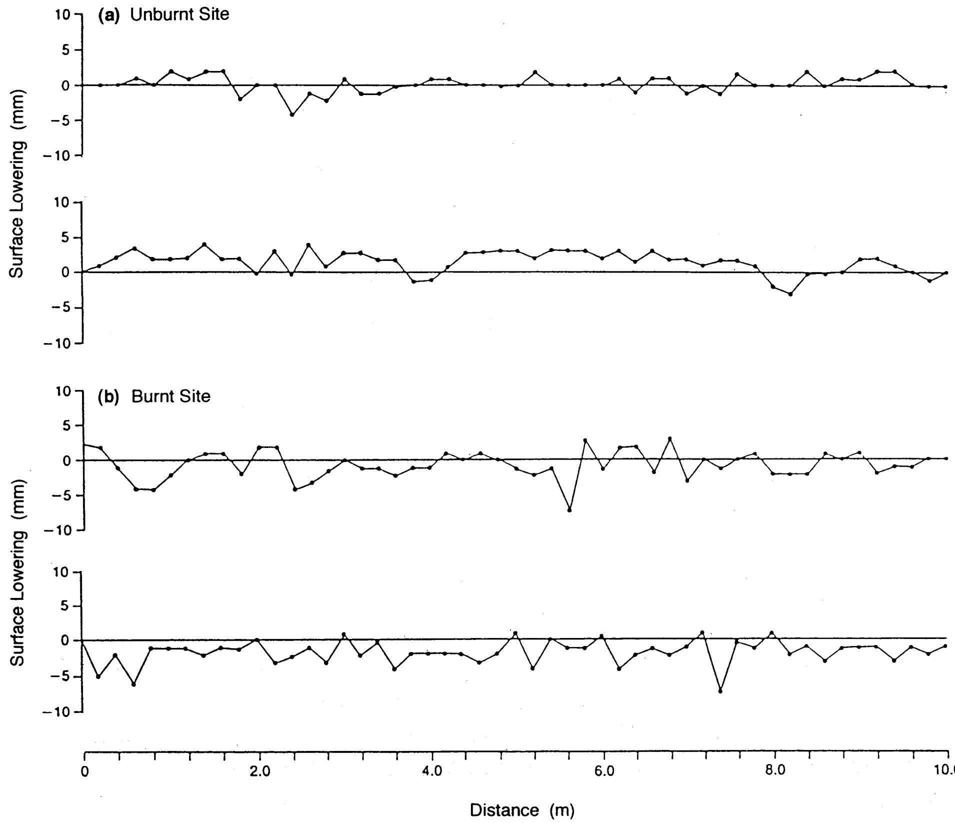

Fig. 2 Surface movement at two erosion pin transects showing net deposition (+0.94 mm) at site (a) and net erosion (−1.24 mm) at site (b). Site (b) was burnt in the previous dry season.

erosion and deposition are occurring, with net accumulation at transect (a) and net erosion transect (b) over a one year period (1980-1981). Net deposition was measured at 24 of the 27 transect sites in the lowlands (Fig. 3).

Although the erosion pin data do not indicate the periods of sediment storage on the lowland slopes, they do suggest that the path of material eroded from the Kombolgie sandstone involves a very long period of slow slope wash across the lowland slopes. Even apparently significant surface movement measured at certain pin sites may reveal nothing more than minor displacement of single gravel particles (the steep deposition peaks depicted in Fig. 2, because they are isolated, probably reflect movement of single gravel particles, which are up to 20 mm diameter).

Global perspective

The wet /dry tropics has among the world's highest recorded sediment yields and rates of water erosion (Saunders & Young, 1983). In the arid zone, erosion and sediment yields are low because of the infrequency of rainfall and runoff. They are low in the humid tropics because of the dense forest cover. In the seasonally wet tropics, however,

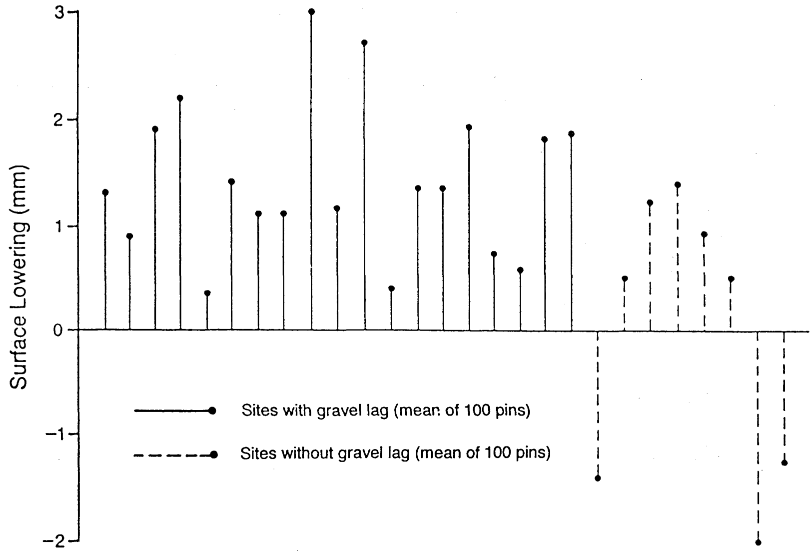

Fig. 3 Net surface movement measured over one year at 27 erosion pin transect sites in the natural lowlands of Kakadu.

high rates of erosion and sediment yield are expected because of the coincidence of sparse vegetation and intense rainfall at the beginning of the wet season. Based on rainfall intensity alone, the Kakadu region would be expected to experience high rates of denudation relative to the rest of the Australian continent (McFarlane & Clinnick, 1984).

The denudation rates estimated from sediment yields in the Kakadu region are an order of magnitude lower than the typical range reported from the wet/dry tropics (100 to 500 mm 1000 years^{-1}; Saunders & Young, 1983) and are comparable to the low rates typical of the Australian continent in general (Olive & Walker, 1982), and of forested, tectonically stable areas of the humid tropics in Australia and Malaysia (Douglas, 1976).

Factors controlling erosion and sediment supply

Although live vegetation cover is sparse, significant litter cover is present on the surface at the beginning of the wet season. Pre-wet season litter cover, even in burnt areas (resulting primarily from leaf and debris fall) is typically greater than 30% and cover of up to 90% has been recorded (mean at 27 erosion pin transect sites was 50%; Duggan, 1989).

The substantial litter cover would act to deflect rain energy and slow down runoff, thereby protecting the surface from erosion. A further influence of litter is the formation of litter dams, particularly on burnt slopes. The litter dams reduce the rate of runoff, and create a stepped microtopography conducive to deposition and storage of sediment. A weak but statistically significant inverse relationship between pre-wet season litter cover and surface lowering ($r = -0.57$; SEE 0.36; significant at the 0.01 level) was found in the erosion pin study reported above (Duggan, 1989).

The litter cover is not, however, the major factor in the stability of the lowland surface. The effect of litter is largely overshadowed by the mechanical resistance to rain splash and surface wash afforded by the surface gravel lag. The most compelling evidence for this is found in what happens when the gravel lag is disturbed.

The erosion pin data show that an increase in the rate of surface lowering may be expected following removal of vegetation cover through burning. Disturbance of the surface lag, however, produces dramatic increases in rates of erosion and rapid gully formation, even on slopes of less than 2°.

DEVELOPMENT IMPACTS

A study of the impact of land clearing at the Ranger and Nabarlek (Fig. 1) uranium mines on erosion and sediment transport was carried out between 1979 and 1987. This study examined hillslope erosion at lowland sites cleared for infrastructure, housing and borrow pits.

The mean rate of surface lowering calculated from monitoring of 2400 erosion pins on disturbed lowland slopes near the Ranger and Nabarlek mines was found to be 1.25 mm $year^{-1}$ (SE 0.32). This is 2 orders of magnitude greater than levels recorded on undisturbed lowland slopes (Fig. 4). Soil loss on steep embankment slopes (17°) at the mine sites ranged from 2.0 to 7.0 mm $year^{-1}$, with the highest value being from an bare earth embankment, and the lowest value from an embankment stabilized with a rock mulch. Values for vegetated embankments fell between these extremes.

The study also involved monitoring of the sediment yields of two mine site (Ranger and Nabarlek mine sites) and one urban drainage basin (Jabiru Township). The three basins, ranging in size from 15 to 22 ha, were monitored for three to four years following clearing and construction of buildings and infrastructure. Annual suspended sediment yield was calculated from flow proportional sampling of runoff at the outlets of the basins. A total of 2049 samples was collected from 316 discharge events in the three basins between 1979 and 1983.

Annual suspended sediment yields of 2000 to 3000 t km^{-1} are recorded for the three disturbed basins during the construction phase (Fig. 5, year 1). These figures compare with yields of less than 70 t km^{-1} recorded for the four undisturbed basins reported above.

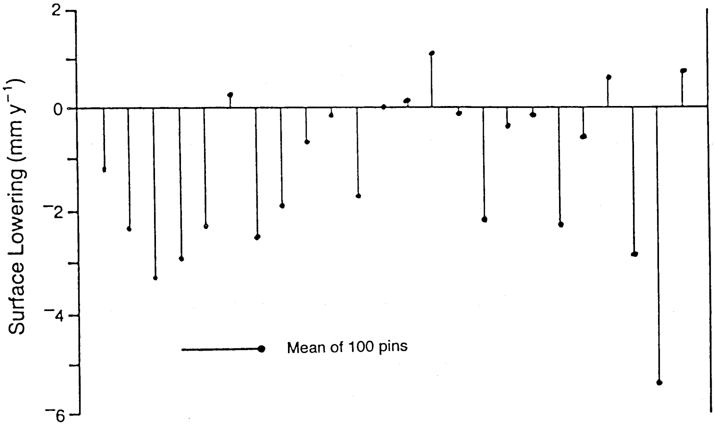

Fig. 4 Net surface movement measured over one year at 24 erosion pin transect sites on disturbed lowland slopes.

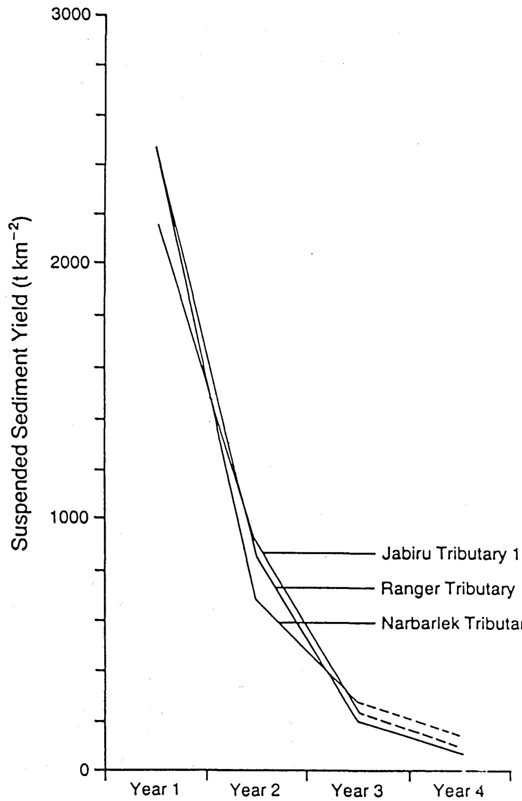

Fig. 5 Annual sediment yields of disturbed lowland drainage basins in the Kakadu region.

Not only was the impact of disturbance evident in the magnitude of sediment yields (which could be influenced by differences in basin area) but also in the nature of the sediment transported. Sediment yields in the disturbed basins comprised large proportions of silt and clay, resulting in highly turbid runoff, in marked contrast to the clear runoff from undisturbed slopes in the region.

Annual suspended sediment yields in the disturbed basins, however, fell dramatically to natural levels within four years (Fig. 5). The fall in sediment yield reflects the progressive establishment and maintenance of (largely exotic) vegetation on the disturbed slopes of the basins. This traditional form of stabilization and erosion control apparently works in the short term, but observations of erosion processes at rehabilitated sites suggest that it is not sustainable in the Kakadu region.

LESSONS FOR REHABILITATION OF DISTURBED SLOPES

Over 60% of total annual erosion on disturbed, bare surfaces occurs in the initial two months of the wet season (Duggan, 1989). Therefore, unless irrigation is used to promote establishment of the exotic ground cover before the onset of the wet season, little is achieved for significant cost in the first year of revegetation.

Much of the fertilizer applied to the rehabilitated areas is also lost during the initial wet season rains. Over 25% of nitrogen and about 90% of potassium applied at a rehabilitated site treated with standard techniques near the Jabiru Township was lost in the first wet season (Duggan, 1989). These nutrients would be washed to nearby streams with the potential hazard of nutrient build-up and associated impacts on the local ecology.

Most importantly, with the combination of dry season drought and fire, the exotic grasses do not persist for longer than about three years unless constantly maintained, and a bare surface is exposed once again to wet season rains as the exotics die out. In effect, the exotic cover established at considerable expense, only serves to delay a high rate of erosion.

The means by which long term stabilization can be achieved in the absence of intensive maintenance of exotic vegetation cover are worthy of investigation. The studies of erosion on natural and disturbed slopes reported above indicate that the primary factor limiting erosion in the lowlands is the coarse surface lag. A crude but demonstrative study of the formation of the surface lag carried out at a rehabilitated site near Jabiru Township showed that the lag will re-establish within one wet season if the surface is reshaped to pre-existing contours, and spread with very gravelly soil (Duggan, 1989). The study involved monitoring of the sediment yield of the rehabilitated site. In addition, rain splash exclusion screens (1 m^2) set 1 m above the ground surface were used to examine lag formation. The lag rapidly formed around the screens but did not form beneath them.

Neither does the lag form under a dense cover of exotic vegetation, because, like the exclusion screens, the vegetation cover absorbs rain splash energy (the main agent in formation of the lag) and prevents selective erosion of fines. While an alternative method of rehabilitation, encouraging rapid formation of a surface gravel lag, promotes a high initial rate of erosion as the lag is forming, the surface is stabilized within one wet season. The resulting stable surface is much more likely to persist in the long term than is an exotic ground cover, and is achieved at considerably less cost.

The same situation applies to the steeper embankment slopes created on mine sites. These are more likely to be stabilized in the long term through re-establishment of the configuration of natural steep slopes in the region. These are armoured by coarse rock. While vegetation cover also plays a role, it is far less significant than the rock armour. These principles need to be understood and applied to rehabilitated sites in the region.

Acknowledgements The data reported in this paper were collected through research projects initiated by the Conservation Commission of the Northern Territory and supported by the University of the Northern Territory and the Alligator Rivers Region Research Institute.

REFERENCES

Douglas, I. (1976) Natural and man-made erosion in the humid tropics of Australia, Malaysia and Singapore. In: *Landforms and Geomorphology: Concepts and History* (ed. by C. A. M King), Benchmark Papers in Geology no. 28, 353-365.

Duggan, K. (1989) Mining and erosion in the Alligator River region of northern Australia. Unpublished PhD thesis, School of Earth Sciences, Macquarie University.

Galloway, R. W. (1976) Geomorphology of the Alligator Rivers Area. In: *Lands of the Alligator Rivers Area, Northern Territory* (ed. by R. Story, R. W. Galloway, J. R. McAlpine, J. M. Aldrick & M. A. J. Williams), Commonwealth Scientific and Industrial Research Organization Land Research Series no. 38, 52-70.

Jackson, I. (1977) *Climate, Water and Agriculture in the Tropics*. Longman, London.

Lee, D. M. & Neal, B. (1984) The climate of northern Australia. In: *Northern Australia: The Arenas of Life and Ecosystems on Half a Continent* (ed. by D. Parkes), 29-55. Academic Press, Sydney.

McAlpine, J. R. (1976) Climate and water balance. In: *Lands of the Alligator Rivers Area, Northern Territory* (ed. by R. Story, R. W. Galloway, J. R. McAlpine, J. M. Aldrick & M. A. J. Williams), Commonwealth Scientific and Industrial Research Organization Land Research Series no. 38, 35-40.

McFarlane, D. J. & Clinnick, P. F. (1984) Annual rainfall erosion index for Australia. *Erosion Research Newsletter* **9**, 3-4.

McGill, A. (1983) Reassessment of the extreme rainfall events in the Alligator Rivers Region. *Environmental Protection in the Alligator Rivers Region*, Supervising Scientist for the Alligator River Region, Scientific Workshop Papers no. 88.

Milnes, A. R., Riley, G. G. & Rowen, M. D. (1986) Rock weathering, landscape development and the fate of uranium in waste-rock dumps and the low grade ore stockpile. In: *Rehabilitation of Waste Rock Dumps, Ranger No. 1 Mine, N.T.*, Commonwealth Scientific and Industrial Research Organization Division of Soils Report, 1-27.

Needham, R. S., Crick, I. H. & Stuart-Smith, P. G. (1980) Regional geology of the Pine Creek Geosyncline. In: *Uranium in the Pine Creek Geosyncline* (Proc. International Uranium Symp. on the Pine Creek Geosyncline, Sydney, June 1974), 1-22. International Atomic Energy Agency, Vienna.

Olive, L. J. & Walker, P. H. (1982) Processes in overland flow-erosion and production of suspended material. In: *Prediction in Water Quality* (ed. by E. M. O'Loughlin & P. Cullen), 87-119. Australian Academy of Science, Canberra.

Saunders, I. & Young, A. (1983) Rates of surface processes on slopes, slope retreat and denudation. *Earth Surf. Processes and Landforms* **8**, 473-501.

Stuart-Smith, P. G., Willis, K., Crick, I. H. & Needham, R. S. (1980) Evolution of the Pine Creek Geosyncline. In: *Uranium in the Pine Creek Geosyncline* (Proc. International Uranium Symp. on the Pine Creek Geosyncline, Sydney, June 1974), 23-27. International Atomic Energy Agency, Vienna.

Williams, M. A. J. (1969) Geomorphology of the Adelaide-Alligator area. In: *Lands of the Adelaide-Alligator Area* (ed. by R. Story, M. A. J. Williams, A. D. L. Hooper, R. E. O'Ferrall & J. R. McAlpine), Commonwealth Scientific and Industrial Research Organization Land Research Series no. 25, 71-93.

Wischmeier, W. H., Smith, D. D. & Uhland, R. E. (1958) Evaluation of factors in the soil loss equation. *Agric. Engng* **39**, 458.

Woodroffe, C. D., Chappell, J. M. A., Thom, B. G. & Wallensky, E. (1985) Geomorphology of the South Alligator tidal river and plains, Northern Territory. In: *Coastal and Tidal Wetlands of the Australian Monsoon Region* (ed. by K. N. Bardsley, J. D. S. Davie & C. D. Woodroffe), Australian National University, North Australian Research Unit Mangrove Monograph no. 1, 3-15.