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Geomorphic research to determine the off-site impacts of the Jabiluka Mine on Swift (Ngarradj) Creek, Northern Territory

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Executive summary

A literature review has found that there is limited background information on the environmental characteristics of the Swift (Ngarradj) Creek catchment, which contains the portal, retention pond and other head works for the Jabiluka uranium mine. To determine the baseline geomorphic characteristics of catchments in the Jabiluka Mineral Lease as well as the physical impacts of uranium mining, 13 sub-projects were proposed within the framework of a sediment budget.

1 **Geomorphic mapping**. The location and characteristics of the channel network and catchment geomorphology should be mapped by differential GPS and air photograph interpretation to produce a detailed geomorphic map of the Swift Creek catchment that can be used for environmental impact assessment of the mine.

2 **River reach definition and mapping**. Morphologically homogeneous channel reaches should be mapped and described throughout the catchment to provide a spatial framework for monitoring and impact assessment and to measure future changes in reach boundaries and/or characteristics. A preliminary classification based on air photograph interpretation and limited field inspections has been produced for further testing and refinement.

3 **Historical channel stability/instability**. The historical stability/instability of each channel reach should be assessed from all available vertical air photographs to provide an understanding of pre-mining channel behaviour and to provide baseline conditions for the assessment of post-mining channel changes.

4 **Fluvial sediments**. Grain size characteristics of channel boundary and floodplain sediments and the volume of the alluvial store should be determined for each channel reach to provide baseline conditions for the assessment of post-mining impacts on sediment movement.

5 **Digital elevation model**. A digital elevation model of the whole catchment should be constructed for landform evolution modelling by SIBERIA for environmental impact assessment, mine management, design of a stable rehabilitated mine site and prediction of mine-derived sediment deposition sites downstream of the mine site.

6 **River gauging stations**. At least four river gauging stations (two on control rivers and two on mine-impacted rivers) with pluviometers should be installed and operated to obtain hydrological information on natural catchment conditions and on the impact of mining. The control rivers are Swift Creek upstream of the mine site and Tributary East. Energy Resources of Australia (ERA) also operate two gauging stations on 7J and North Magela Creeks, which are appropriate controls, if they are not impacted by road construction. The mine-impacted stations are Swift Creek downstream of the mine site and Tributary Central.

7 **Suspended sediment transport and turbidity**. Detailed suspended sediment and turbidity measurements should be undertaken at each ***eriss*** river gauging station to calculate natural and mine-induced suspended sediment loads during the Wet season.

8 **Bedload transport**. Detailed bedload measurements should be undertaken at each ***eriss*** river gauging station to calculate natural and mine-induced bed-material loads. Bedload constitutes a large proportion of the total sediment load in the Alligator Rivers Region and is essential for an assessment of the impact of mining on total sediment yield.

9 **Bed scour depths**. Scour chains should be installed and measured annually at each gauging station and on mine site tributaries to determine the maximum depth of bed scour (active bedload) during each Wet season.

10 **Contemporary channel erosion rates**. Bank erosion and knickpoint migration rates should be selectively measured to determine the significance of in-channel sediment sources in comparison to the sediment yields generated on the mine site and from the undisturbed catchment.

11 **Contemporary channel stability**. Permanently marked cross sections should be installed and used to monitor the amount of bed sediment storage and/or large scale channel erosion throughout the river network.

12 **Sediment storages**. The volume of sediment in discrete sediment storages downstream of the mine site should be mapped and measured.

13 **Riparian vegetation and large woody debris**. The significance of riparian forests and large woody debris for stabilising sinuous sandy channels and storing bed material on Swift Creek and East Tributary should be evaluated.

These projects were proposed, described and initiated at short notice before the commencement of the 1998/1999 Wet season. This was necessary to ensure that some catchment characteristics had been measured before the first flush of the Wet season after initial disturbance for mine establishment. No program of hydrologic and geomorphic research had been commenced in the Swift Creek catchment by ***eriss*** before June 1998. Furthermore, initial geomorphic measurements of the mine site tributaries and Swift Creek were also required before the first flush of the 1998/1999 Wet season to help determine the environmental impacts of mining.

The above projects target channel stability/instability, sediment sources, sediment storages, sediment pathways and sediment fluxes within the channel network of Swift Creek. Sites impacted by uranium mining will be compared with similar natural sites upstream of the influence of mining. A standard or modified BACI (Before After Control Impact) design was not possible because mining had started before any of the projects could be implemented.

Key Words: Jabiluka, uranium mining, geomorphic mapping, river reaches, sediment storages, channel erosion, river gauging, suspended sediment, turbidity, bedload, hydrology, GIS, digital elevation model.

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Glossary

The purpose of this Glossary is to define the hydrologic, geomorphic and sedimentologic terms used in this report.

Alluvial fan. This is an accumulation of sediment that has been deposited where a sediment-laden stream emerges from a confined upland valley onto a piedmont where it spreads laterally and deposits its load as a semicircular sediment body (Schumm et al 1987).

Anabranch. This is a relatively long channel that separates from the main stream and usually rejoins it downstream. In some cases, such branches may join another river. Anabranches are usually separated from the main channel by floodplain (Schumm et al 1996).

Avulsion. The abrupt, wholesale abandonment of a relatively long reach of river for a new location, usually at a lower elevation on the floodplain (Schumm et al 1996).

Bankfull. The stage at which the floodplain first gets inundated (ie the channel-floodplain junction) and which often corresponds to the minimum width-maximum depth ratio for a channel cross section (Riley 1972).

Bar. This is a large scale bedform which has a length of the same order as the channel width or greater, and a height comparable to the mean depth of the generating flow (Brush et al 1966).

Base flow. This refers to relatively low, progressively diminishing streamflows produced by soil water and groundwater drainage to a stream. In the Alligator Rivers Region, base flows are relatively high during the Wet season but slowly decline to zero as the soil water and groundwater stores are progressively depleted during the onset of the Dry season.

Bedform. This is a geometric configuration of bed material on the river bed surface that is more than one grain diameter high and that is formed by the flow. Large scale bedforms have lengths at least equivalent to channel width and heights comparable to the mean depth of the generating flow (Brush et al 1966). Small scale bedforms have lengths less than channel width and heights much less than bankfull depth.

Bench. This is a depositional landform which is an essentially tabular, often vegetated, elongate, usually discontinuous, sometimes paired, usually bank-attached sediment body and which occurs at intermediate elevations between the river bed and the main valley flat level (Erskine & Livingstone 1999). Benches develop at various locations within the channel (Erskine & Livingstone 1999), most commonly in straight reaches as parallel benches, on the inside of bends as crescentic point benches, which often extend away form the bend to join parallel benches, and less commonly, along the outside of bends as concave benches (Woodyer 1975).

Billabong. This is a standing body of water that has formed either within a river channel or on the floodplain. They are formed either by scour or impoundment and Hart and McGregor (1982) recognised three types on Magela Creek, namely backflow billabongs, channel billabongs and floodplain billabongs.

Braided river. These are relatively steep, straight, wide rivers with multiple, often laterally shifting thalwegs separated by numerous bars.

Channel control. A stable channel cross section, such as a riffle or a constriction, that determines the upstream gauge height-discharge relationship in the backwater-affected area.

Clay. This refers to sediment with a diameter less than 0.0039 mm (Wentworth grain size scale).

Control structure. This is a precisely constructed weir or flume with known hydrodynamic behaviour that is theoretically rated by a weir or flume equation.

Fan delta. This is an alluvial fan that progrades into a body of water from an adjacent highland. A fan delta has many of the surface characteristics of an alluvial fan and many of the subaqueous characteristics of a delta (Schumm et al 1987).

Floodout. This is a valley-floor zone where most flows are incompetent to transport the bed material, resulting in a fan-like form of aggradation (Erskine & Melville 1983a). Deposition and drainage disorganisation are caused by a substantial reduction in flow velocity and channel capacity as the channel approaches the intersection point (Erskine & Melville 1983a). Intermediate floodouts where channels reform downstream (Tooth 1999), are characteristic of the Swift Creek catchment.

Floodplain. This is a relatively flat alluvial plain bordering a river channel and subject to periodic flooding.

Gravel. This refers to sediment with a diameter greater than 2 mm (Wentworth grain size scale).

Gully. This is a relatively deep, recently formed, eroded channel that is cut into unconsolidated sediment where no well defined channel previously existed (Schumm et al 1984).

Intersection point. The distal end of a channel where the bed and bank profiles intersect, extinguishing the channel. They are associated with alluvial fans and floodouts (Erskine & Melville 1983a).

Knickpoint. This is a zone where bed slope increases abruptly (Brush & Wolman 1960). Primary knickpoints at the upstream limit of a gully are often vertical falls whereas secondary knickpoints are steep sections of the gully bed eroding temporarily stored sediment.

Meandering river. These rivers have a sinuosity of at least 1.5, a series of regular bends with alternating curvature, large-scale pool-riffle bedforms and point bars on the inside of bends.

Plunge pool. This is a relatively deep scour pool eroded at the base of a waterfall or a knickpoint and enclosed by an arcuate downstream bar of sediment eroded from the plunge pool.

Point bar. This is a largely unvegetated body of sediment within the channel against the convex (inside) bank of a bend (Nanson 1980).

Pool. This is a large-scale bedform that is a relatively deep part of the river bed with a flat water surface profile and slow flow under base flow and which is floored with relatively fine sediments. Pools usually alternate with riffles in gravel bed streams and are rhythmically spaced at about 5–7 channel widths.

Rating curve. The relationship between gauge height and discharge established at a gauging station by a number of velocity-area gaugings over a range of gauge heights. It is used to convert continuously recorded gauge heights into a continuous discharge record.

Riffle. This is a large-scale bedform that is a relatively shallow part of the river bed with a steep water surface profile and fast flow under base flow and which is floored with relatively coarse sediment. Riffles usually alternate with pools in gravel bed streams and are rhythmically spaced at about 5–7 channel widths. Generally they are areas of subcritical flow modified by local free-surface instabilities and small hydraulic jumps over bed roughness element (Grant et al 1990). Only 5–10% of the water surface area exhibits supercritical flow (Grant et al 1990).

River reach. This is a length of river exhibiting relatively homogeneous channel characteristics or a consistent pattern of repetitive/alternating characteristics.

Run. This is a large-scale bedform that is intermediate between pools and riffles under base flow. It is characterised by uniform steady flow because the bed and water surface profiles are parallel. Glides are also recognised as a less turbulent and less steep version of a run.

Sand. This refers to sediment with a diameter between 0.0625 and 2 mm (Wentworth grain size scale).

Secondary channel. This is a channel which is much smaller than the main stream.

Silt. This refers to sediment with a diameter between 0.0039 and 0.0625 mm (Wentworth grain size scale).

Sinuosity. This refers to the ratio of channel length to valley length. It may also be expressed as the ratio of channel slope to valley slope and is essentially a measure of the degree of meandering.

Thalweg. This is the path followed by the line of maximum flow velocity (Rhoads & Welford 1991). While the thalweg usually follows the path of maximum depth, this is not necessarily the case when secondary channels are present (Wolman & Brush 1961).

Tributary-mouth bar. This is a downstream elongated sediment body that originates at the confluence of one usually smaller channel with another (Petts 1984).

Velocity-area gauging. This is the field measurement of the mean flow velocity by a current meter and cross sectional area by tape and wading rod for a specific gauge height at a stable gauging site. The results of a number of velocity-area gaugings for a range of gauge heights are needed to construct a reliable rating curve.

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1 Introduction

In October 1996 Energy Resources of Australia (ERA) submitted a Draft Environmental Impact Statement (Kinhill Engineers & ERA Environmental Services 1996) for the mining of uranium at Jabiluka. The Commonwealth Government approved the Ranger Mill Alternative in October 1997 subject to a broad range of requirements on environmental protection (Johnston & Prendergast 1999). The Ranger Mill Alternative involved the mining of the Jabiluka orebody by underground methods and the milling of the ore at the existing mill at Ranger (Kinhill Engineers & ERA Environmental Services 1996). However, following the refusal of the traditional land owners to permit the trucking of ore from Jabiluka to Ranger, 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). This alternative involved the construction of a new mill at Jabiluka and was outlined in a Public Environment Report (Kinhill & Energy Resources of Australia Ltd 1998). Environmental requirements stipulated that all mill tailings had to be returned to the underground mine void and to specially constructed stopes or silos instead of tailings pits, as proposed by ERA (Johnston & Prendergast 1999). Work on the mine began immediately after government approval. Despite criticisms of the Jabiluka Mill Alternative by Wasson et al (1998) which were also raised by the World Heritage Committee, the Supervising Scientist found that development of the Jabiluka uranium mine will not threaten the natural values of Kakadu National Park (Johnston & Prendergast 1999). The Jabiluka Mining Lease is surrounded on three sides by Kakadu National Park and by the Ranger Mining Lease on the fourth.

As outlined below, there are limited data on catchment geomorphology, channel stability/instability, sediment movement and hydrology of the Swift Creek[1] catchment, which contains the portal, retention pond and other head works for the Jabiluka Mine (fig 1). There was an urgent need to establish baseline channel, sediment and hydrological conditions to assess changes caused by the commencement of mining before the first flush of the 1998/99 Wet season. Furthermore, two small creeks were at least partly diverted from their natural course through sections of artificial channel to enable the construction of mine infrastructure. Therefore, baseline conditions had to be determined before the start of streamflow for the 1998/99 Wet season to avoid measuring any impacts of the mine. The channel network is the conduit for runoff, sediment and pollutants leaving the mine site, and the mine site tributaries (fig 1) will be the first part of the catchment to experience off-site environmental impacts. It is

[1] The name Swift Creek is used in this report for the river that drains the catchment in which the Jabiluka Mine is located and that flows into the Magela Creek wetlands. Ngarradj is the Aboriginal name for this stream system. The full term is Ngarradj Warde Djobkeng and is the site where the cockatoo vomited on and split the rocks to form the creek known as Ngarradj. It is one of several dreaming (Djang) sites on or adjacent to the Jabiluka mine lease (A Ralph, Gundjehmi Aboriginal Corporation, 2001).

also necessary to characterise the catchment, channels and hillslopes so as to establish a temporal and spatial data base as part of a Geographical Information System (GIS) on sediment movement for long-term land and water management. Research by the Environmental Impact of Mining Section of ***eriss*** should address the incorporation of modelling techniques into the GIS which can use catchment, channel, hydrological and sediment data for the calibration of landform evolution and sediment transport models (SIBERIA).

These models are needed for:

1 Prediction of the long-term impacts of mining; and

2 Selection of stable post-mining landforms as part of mine decommissioning and rehabilitation.

It is essential that data for model calibration are collected so that alternative mine rehabilitation plans can be reliably evaluated before mine decommissioning.

This report outlines 13 sub-projects that were developed at short notice in 1998 to determine the off-site geomorphic impacts of the Jabiluka uranium mine on Swift Creek. Pickup et al (1987) noted that their feasibility study of geomorphic research for the long-term management of uranium mill tailings at Ranger uranium mine discussed many issues that could equally apply to Jabiluka. Some of these have been modified below in their application to Jabiluka. Erskine and Saynor (2000) also concluded that the geomorphic behaviour and sediment dynamics of the Ranger Mine site tributaries were not well understood, despite being the initial storages and pathways for mine-derived particulates. The projects proposed below address these issues for the Jabiluka Mine.

2 Aims

The aims of this project are threefold, namely:

1 To review existing literature on the geomorphology, geology, soils, climate and hydrology of the Swift Creek catchment;

2 To develop projects for obtaining baseline data on the channel network, channel stability/instability, channel boundary sediments, sediment storages, sediment fluxes and hydrology of the Swift Creek catchment; and

3 To outline projects for determining temporal changes in channel morphology and aquatic habitat, sediment storages, sediment fluxes and hydrology due to mining.

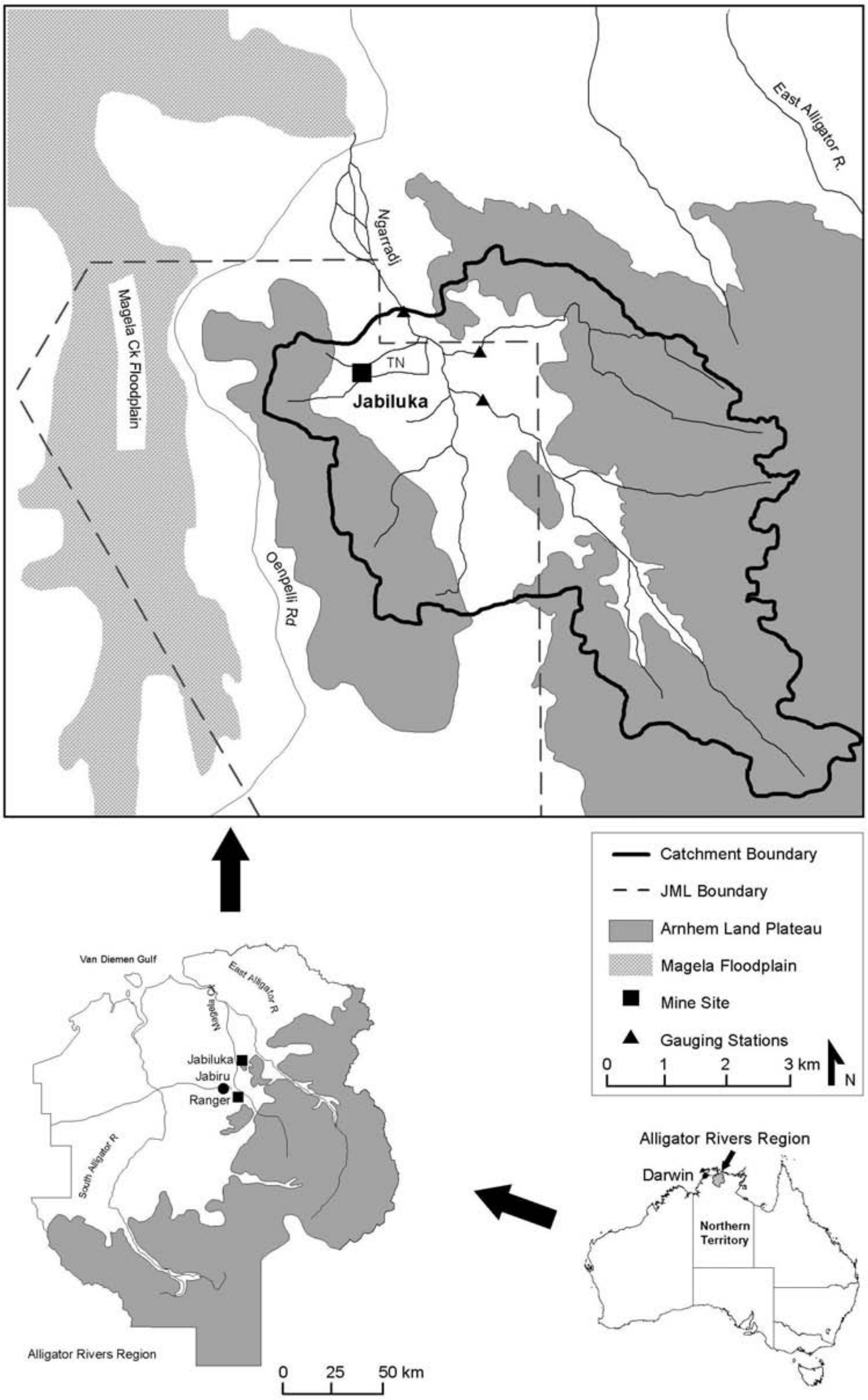

Figure 1 The Swift Creek catchment showing the Jabiluka Mineral Lease (JML), gauging stations and local creek names. SC refers to Swift Creek gauging station, TN Tributary North, ET East Tributary gauging station, TC Tributary Central, TS Tributary South, TW Tributary West and UM upper Swift Creek gauging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

3 Outline

To determine the baseline characteristics of catchments in the Jabiluka Mineral Lease and the hydrologic and geomorphic impacts of uranium mining, the following 13 sub-projects were proposed for implementation:

1 A detailed geomorphic map of the catchment;

2 Mapping and description of morphologically homogeneous channel reaches throughout the Swift Creek catchment;

3 Assessment of historical stability/instability of each channel reach from all available vertical air photographs;

4 Determination of the grain size of channel boundary and floodplain sediments for each channel reach;

5 Construction of a digital elevation model (DEM) of the whole Swift Creek catchment;

6 Installation and operation of at least four river gauging stations and pluviometers (two on control rivers and two on mine-impacted rivers);

7 Detailed suspended sediment and turbidity measurements at each river gauging station;

8 Detailed bedload measurements at each river gauging station;

9 Installation and measurement annually of scour chains at each gauging station and on mine site tributaries;

10 Selective measurement of bank erosion and knickpoint migration rates;

11 Installation of permanently marked cross sections throughout the channel network;

12 Mapping and measurement of the volume of sediment in discrete sediment storages downstream of the mine site;

13 Evaluation of the significance of riparian forests and large woody debris for stabilising sandy channels and storing bed material on Swift Creek and Tributary East.

Each of these sub-projects is outlined in detail with appropriate methodologies in section 6.

The available background information on Swift Creek is outlined below. Each of the activities required to establish the baseline characteristics of the catchment, as well as the impact of uranium mining, is detailed along with the observations and data collected during field work. The purpose of this report is to outline the purpose, design and methodology for each sub-project. Results for any project that is implemented will be published in subsequent Supervising Scientist Reports.

4 Background information

There is limited background information on the environmental characteristics of the Swift Creek catchment. The available information is contained in the following sources:

- **Topographic maps**: The largest scale available are two 1:50 000 maps ('Mount Brockman' 5472 1; 'Canon Hill' 5473 2) that were printed in 1997 by Army Topographic Support Establishment. There are also two 1:100 000 maps ('East Alligator' Sheet 5473 1st Edition produced by Division of National Mapping in 1971 and 'Cahill' Sheet 5472 2nd Edition produced by Royal Australian Survey Corps in 1976) and one 1:250 000 map

(‘Alligator River’ SD 53-1 1st Edition compiled by Royal Australian Survey Corps in 1984) that cover the Swift Creek catchment.

- **Vertical aerial photographs**: ***eriss*** has copies of aerial photography (contact prints) flown at the times detailed in table 1. In addition, copies of Energy Resources of Australia Ltd 1:5000 Rectified Photomap Ranger-Jabiluka Sheets 1 and 2 derived from air photographs flown in August 1997 have also been obtained. Digital copies are being sought for input into Arcview to provide a base map for a GIS. Data obtained using a differential Global Positioning System (dGPS) will be superimposed on the rectified photomaps.

  Available vertical air photographs need to be obtained as part of the baseline characterisation, provided they are at an appropriate scale of 1:15 000 to 1:40 000. Needham (1984) lists vertical air photographs flown by various authorities in 1968, 1969 and 1972 that may cover the Swift Creek catchment. Flight diagrams of all runs should be obtained to determine whether they cover the Swift Creek catchment. There are also photographs held by Auslig, which were flown on 20 May 1984.

Table 1 Aerial photography of the Swift Creek catchment held by ***eriss***

Date	Run	Photographs
16 May 1950	7	5012–5015, inclusive
	8	5060–5063, inclusive
27 June 1964	20	5090–5095, inclusive
	21	5117–5122, inclusive
	22	5109–5115, inclusive
16 July 1964	22AE	5060–5066, inclusive
22 June 1975	13	3124–3127, inclusive
	14	3135–3140, inclusive
8 July 1975	15	5219–5224, inclusive
5 June 1981	12E	165–169, inclusive
5 July 1981	11	70–73, inclusive
13 July 1987	2	75
	3	27–30, inclusive
20 August 1991	3	37–38, inclusive
	4	57–62, inclusive
15 June 1996	4	35–39, inclusive
	5	22–29, inclusive

- **Other remotely sensed data**: Landsat, SPOT and other remotely sensed data have been used in various land management projects in Kakadu National Park. ***eriss*** has access to a comprehensive satellite imagery archive stored at the Environmental Resources Information Network (ERIN) in Canberra. These images include the Swift Creek catchment.

- **Geological maps**: The Swift Creek catchment is covered by:

  i) The 1:500 000 Pine Creek geosyncline map of Needham and Stuart-Smith (1984);

  ii) The 1:250 000 geology maps of Needham (1984, 1988); and

  iii) The ‘East Alligator’ and ‘Cahill’ 100 000 geology maps.

Kinhill Engineers and ERA Environmental Services (1996) repeat the 1:100 000 geology maps.

- **Land resources maps and data**: Land systems and associated climatic conditions, vegetation, soils and landforms of the Swift Creek catchment have been presented and/or mapped at various scales by Christian and Stewart (1953) and Story et al (1969, 1976).

Additional land resources information is contained in the various environmental studies prepared for the mining companies (Pancontinental Mining Ltd 1977, 1979, 1981, Bettenay et al 1981, Kinhill Engineers & ERA Environmental Services 1996, Unger et al 1996, Kinhill & Energy Resources of Australia Ltd 1998) and by Wells (1979).

As a result of limited available data, it is necessary to collect basic climatic, hydrological, sediment transport, stratigraphic and geomorphic information for the following sub-projects. ERA maintains a climate station at the Jabiluka mine site and other neighbouring stations should be sourced and all relevant data obtained. Rainfall stations located within the region are listed in table 2 with the custodian of the information. At some stations, further instrumentation was installed to measure additional climate parameters. In particular, the Australian Bureau of Meteorology usually installs automatic weather stations (AWS) that measure other climatic parameters such as temperature, wind speed and direction, air pressure and humidity.

5 Swift Creek catchment characteristics

5.1 Climate

The Swift Creek catchment is located in the summer rainfall-tropical climatic zone, 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 1971–92) 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 was 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. On average, one cyclone per year affects the Northern Territory coast (McDonald & McAlpine 1991).

5.2 Landforms

The north west part of the Swift Creek catchment comprises the Arnhem Land plateau, which is an exhumed, essentially sandstone, tabular upland (East 1996). A deeply incised, trellised drainage pattern has developed along the closely spaced joints and faults. The scenically striking Arnhem escarpment marks the edge of the plateau and forms the northeastern rim of the Swift Creek valley. Rivers leaving the plateau flow either over steep bedrock falls (East Tributary) or dissect the scarp by long narrow deep sandstone valleys which follow joints and faults (Swift Creek). Steep sandstone slopes with lower scarps, part of the Jabiluka outlier, characterise the southern side of the valley. A low saddle, from which the sandstone has been totally eroded, separates Swift Creek from the adjoining 7J Creek catchment to the south.

Table 2 Rainfall stations located in the Alligator Rivers Region

Site	Station number	Start of record	End of record
Bureau of Meteorology			
Jabiru Airport	014198	1971	1990
Jabiru Airport AWS	014198	1995	Present
Jabiru Town	014208	1983	Present
Gunbalanya (Oenpelli)	014042	1910	Present
South Alligator	014284	1995	Present
Cooinda	014256	1991	1996
Border Store	014271	No data	
Mount Borradaille	014286	No data	
Environmental Research Institute of the Supervising Scientist			
Jabiru East		July 1997	Present
Nabarlek		Nov 1995	Present
Djarr Djarr		Oct 1997	Present
East Alligator		Nov 1997	Present
Mudjinberri		Nov 1999	Present
Swift Creek		Dec 1998	Present
Upper Main (Swift Creek)		Dec 1998	Present
East Tributary (Swift Creek)		Dec 1998	Present
ERA Ranger Mine			
Jabiluka		Aug 1994	Present
Jabiru Airstrip		Jan 1971	Present
Ja Ja		1978	1991
Tailings Dam		Mar 1991	Present
Ore Body No 3		Mar 1991	Present
Queensland Mines Ltd			
Nabarlek Station 1		Jan 1979	Oct 1995
Nabarlek Station 2		Sep 1981	June 1995

Extensive colluvial footslopes and fans have accumulated between the sandstone outcrops and contemporary floodplains. Near the escarpment, Roberts (1991) found that sand fans in this area 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. The extensive undulating lowlands to the west of Jabiluka are part of the Northern Lateritic Plains of Christian and Stewart (1953) or the lateritised Koolpinyah Surface of Hays (1967), which has an age range from Proterozoic to Pleistocene (Erskine & Saynor 2000). This geomorphic surface is contiguous with the footslopes and fans in the Jabiluka area (Williams 1969).

Rivers have cut shallow trenches into the footslopes and fans, and extensive Wet season saturation zones have developed in depressions on the footslopes. These alluvial plains are composed of channels, floodplains, billabongs, permanent wetlands and ephemeral swamps.

Late Quaternary estuarine sediments are present at shallow depth below the terminal wetlands at the downstream end of Swift Creek (Clark et al 1992).

5.3 Geology and soils

The Arnhem Land plateau and escarpment and the Jabiluka outlier are composed of resistant, horizontally bedded, vertically jointed, quartz sandstone of the Middle Proterozoic Kombolgie Formation. These rocks belong to the Katherine River Group and were deposited in the McArthur Basin (Needham 1988). The units mapped on the 1:100 000 geological maps in the Ngarradj catchment are Phk_l and Phk_{lf}, which are the lower sandstone sequence below the Nungbalgarri Volcanic Member (Needham 1988). Phk_l is comprised of massive to flaggy quartz sandstone, minor siltstone, tuffaceous siltstone, breccia, conglomerate and cross bedded and ripple marked hematitic and brown ferruginous sandstone. Phk_{lf} is mapped on the Jabiluka outlier and is composed of strongly ferruginous, medium quartz sandstone. The sandstone is generally more than 95% medium to coarse grained, moderately well sorted, subrounded to subangular quartz grains with minor lithic fragments of quartzite and quartz-feldspar granophyric intergrowths (Needham 1988).

Only general soil descriptions corresponding to Great Soil Groups were included for each land system in Christian and Stewart (1953) and are too broad to be applied to Jabiluka. Subsequent soil mapping by Hooper (1969) and Aldrick (1976) used Northcote's (1971) principal profile forms and defined soil families. However, the accompanying soil maps were published at a scale of 1:500 000 and only indicate generalised soil distributions. More detailed interpretations of this information is presented below in the section on land systems. Wells (1979) mapped the soils of 38 km^2 of the Jabiluka Mineral Lease in greater detail using the Northcote (1971) key. The area surrounding the Jabiluka mine exhibits very shallow sands on steep sandstone slopes, shallow red or brown uniform sands at the base of bedrock outcrops and deep uniform sands on the footslopes. The regolith of the footslopes and fans is comprised largely of quartz sand and overlies deeply weathered lateritic saprolites (Bettenay et al 1981). Lateritic pallid zones are dominated by kaolinite in the clay fraction while the yellow and red sandy clays and mottled zones are largely kaolinite with some haematite and/or goethite (Bettanay et al 1981).

The alluvial plains of Swift Creek have not been investigated to date. Preliminary hand auger holes in the Swift Creek floodplain immediately downstream of the mine site revealed at least 3 m of quartz sand that varied from fine to very coarse in grain size. Additional work is in progress on Swift Creek, East Tributary and the mine site tributaries. Silt and mud dominate in the terminal wetlands.

5.4 Land systems

Although Christian and Stewart (1953) produced a 1:1 000 000 land systems map that included three land systems in the Jabiluka area, subsequent work by Story et al (1969, 1976) was published at a scale of 1:250 000 and showed seven land systems. Each land system is briefly described below and their distribution is shown in figure 2.

The **Buldiva land system** is found on the quartz sandstone of the Arnhem Land plateau and escarpment, and exhibits up to six land units (Williams et al 1969, Galloway et al 1976). These land units are the rocky plateau surface with rare thin soils and grassland/savannah vegetation; coarse sandy wash slopes with uniform coarse textured and gradational soils, and eucalypt woodland and savannah; minor erosional remnants and sandstone blocks with skeletal soils and woodland; deep joint-controlled gorges with skeletal soils and semi-deciduous forest; sandstone scarp face with woodland; and scree slopes with shallow sandy soils and woodland.

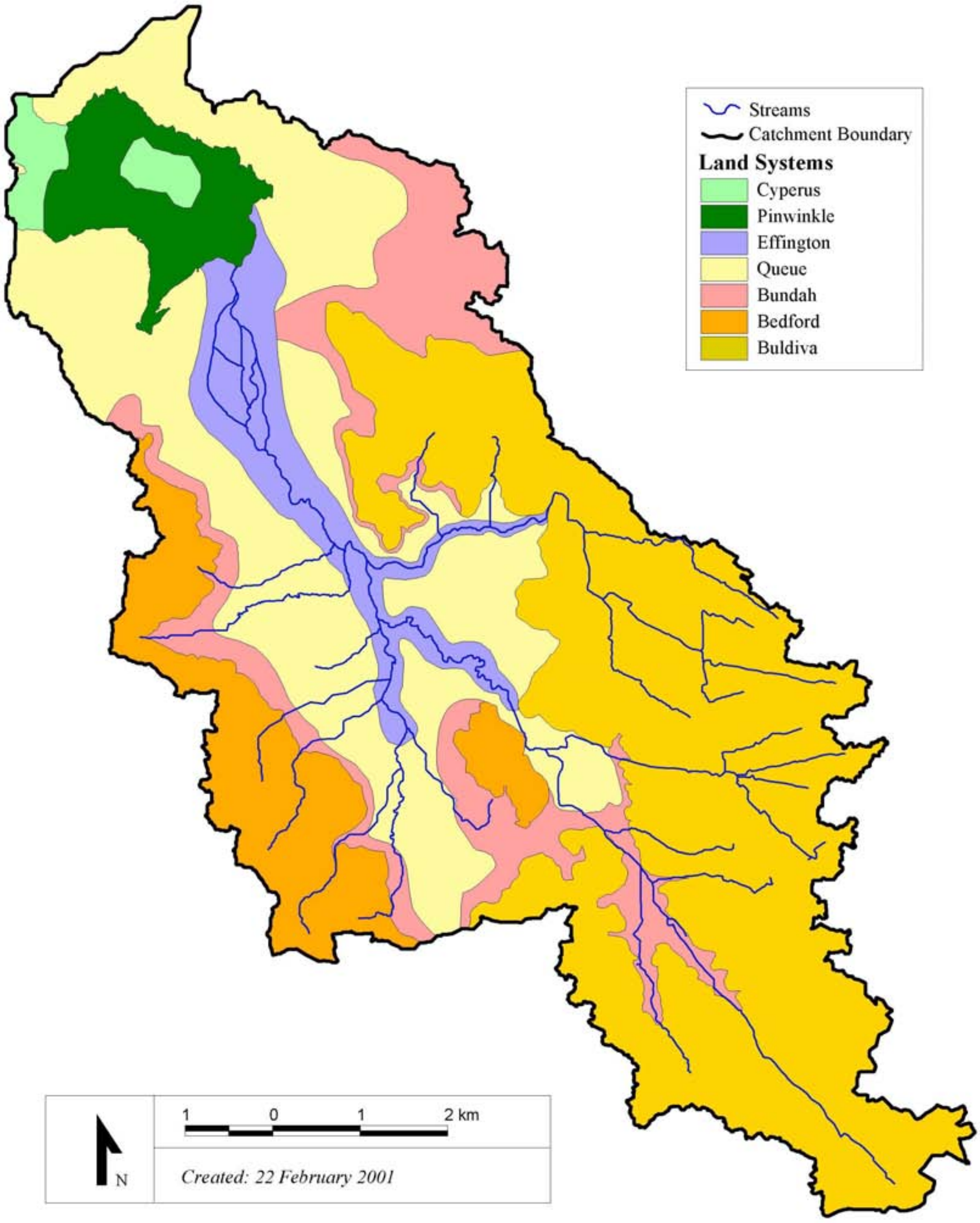

Figure 2 Distribution of the land systems of Story et al (1969, 1976) in the Swift Creek catchment

The **Bedford land system** is also found on the quartz sandstone of the Arnhem Land plateau in more dissected terrain than the Buldiva land system. Galloway et al (1976) described the following three land units: ravines, cliffs, screes and tors with skeletal soils and deep reddish sand, and *Allosyncarpia* forest; sandy colluvial wash slopes with deep siliceous sand and *Allosyncarpia* forest; and highly dissected tableland with skeletal soils and scrub and woodland.

The **Bundah land system** is found on the sandy footslopes and fans below the Arnhem escarpment, and exhibits two land units (Galloway et al 1976). Sandy aprons with sandstone boulders have skeletal soils with wet sands on lower slopes and with mixed scrub or eucalypt woodland; and alluvial fans have wet sandy humic gleys or moist organic brown earths with mixed scrub and non-eucalypt woodland.

The **Queue land system** is found on level to gently undulating sand sheets of the Koolpinyah Surface and exhibits three land units (Williams et al 1969, Galloway et al 1976). Gently undulating to level terrain has deep red and yellow siliceous sands with tall open forest; colluvial aprons and shallow depressions have moderately deep yellow sands with woodland; and unchanneled alluvial flats have humic gleys and wet peaty sands with sedgeland/woodland.

The **Effington land system** is found on sandy floodplains away from the Arnhem escarpment and has a number of land units (Williams et al 1969, Galloway et al 1976). These units cover channels, billabongs, levees, backswamps, terraces and palaeochannels. Sands or muds dominate depending on the depositional environment.

The **Pinwinkle land system** is found at the upstream part of the terminal wetland and consists of black uniform cracking clays over gleyed estuarine muds with tall open forest and annual grasses.

The **Cyperus land system** is found at the downstream part of the terminal wetland and is similar to the Pinwinkle land system, except for the absence of tall open forest.

6 Details of essential catchment baseline and impact assessment studies

6.1 Experimental design

At the time that these projects were being developed during the 1998 Dry season, construction of the portal, retention pond and other head works for the Jabiluka Mine had commenced. Therefore, it was not possible to use a standard or modified BACI (Before After Control Impact) design because no pre-mining work was possible. A sediment budget approach (Reid & Dunne 1996) is suggested to both characterise baseline conditions and to determine the impacts of the Jabiluka mine on sediment movement in the Swift Creek catchment. In particular, the main components of such a project would be to determine:

- the relative importance of different sediment sources (ie the mine versus the rest of the catchment);
- controls on the stability/instability of the channel network and the effects of mining on these controls;
- the pathways of sediment movement from the mine site to Magela Creek;
- channel boundary and floodplain sediments and their changes over time throughout the channel network;
- the location and stability of sediment storages between the mine site and Magela Creek;
- fluxes of mud and sand (suspended sediment and bedload transport dynamics and rates) and the impact of mining on these fluxes.

The main basis of the sub-projects outlined below is a comparison of change between mine-impacted (treatment) and non mine-impacted sites (control). The control sites are needed to estimate the natural sediment exports from the mine site that will be compared with measured values. Budget and personnel constraints are an important consideration when establishing projects as described below. It is anticipated that the sub-projects involving the measurement of hydrological and geomorphic processes should run for at least three years when the results would be evaluated. This evaluation will determine whether any of the sub-projects should continue.

6.2 Geomorphic map of the catchment and channel network

Currently available topographic maps either do not show all of the channel network or depict it incorrectly (ie some channels are not shown at all, and some channels are shown in the wrong location). This limits the use and application of the DEM and erosion models when input data are known to be incorrect. Sediment routing requires an accurate representation of the channel network. The dGPS mapping should be combined with air photograph interpretation to produce an accurate and detailed geomorphic map of the whole Swift Creek catchment. Particular attention must be devoted to accurately defining the channel network, channel connectivity and discontinuous channels, secondary channels and anabranches, channel and floodplain sediment storages, pools and billabongs, bars, knickpoints in unconsolidated valley-fill sediments, plunge pools at the base of knickpoints, intersection point deposits, alluvial fans and eroded river and gully banks. These landforms are defined in the Glossary. The geomorphic map must be integrated with the GIS so that it can be used for assessment and prediction of short-term landform changes (1–5 years) and landform evolution modelling by SIBERIA (Evans et al 1998, Willgoose & Riley 1998) over longer-term periods (1000 years). Changes in the channel network, as well as in particular drainage features caused by mining, road construction, floods and fire should be mapped by dGPS during each Dry season. A preliminary geomorphic map prepared by air photograph interpretation has been completed using the August 1991 1:10 000 prints (fig 3) and should be updated as additional work is completed.

Swift Creek flows in a well-defined valley in a northwesterly direction from the Arnhem Land plateau near the Magela trigonometric station (NTS019) (at grid reference E281700, N8614000 1: 50 000 Mt Brockman Sheet 5472-1) to the Magela Creek floodplain (fig 1). One major tributary (herein called East Tributary) joins Swift Creek on the right bank (fig 3). The names assigned in this report to the channels comprising the Swift Creek channel network are provisional, pending further work on appropriate Aboriginal names. As a result, general geographic names are used. East Tributary has a continuous channel from the Arnhem Land plateau to the main stream. The left bank tributaries of Swift Creek are smaller, usually discontinuous, and exhibit complex morphology. Jabiluka mine is located near the apex of a large alluvial fan drained by three channels, called Tributaries South, Central and North. Tributary West is the largest of the left bank tributaries and drains the saddle, which separates Swift Creek from the adjoining 7J Creek.

A sandy billabong, approximately 200–300 m long, is located on the left bank floodplain of Swift Creek upstream of the mine site. This billabong is a deep pool containing permanent water and large areas of sand, especially at the downstream end. A continuous shallow anabranch parallels Swift Creek from this billabong downstream for about 1.5 km. Tributary Central, which drains part of the mine site, flows into the anabranch. Tributary North, which also drains part of the mine site, flows into Swift Creek downstream of the anabranch and downstream of the confluence with East Tributary. The Swift Creek channel below the junction with the mine site creeks is a single thread, sand-bed stream and ERA has established a river gauging station at the upstream end of this reach. Below this reach the creek becomes a large sand storage zone, as discussed below.

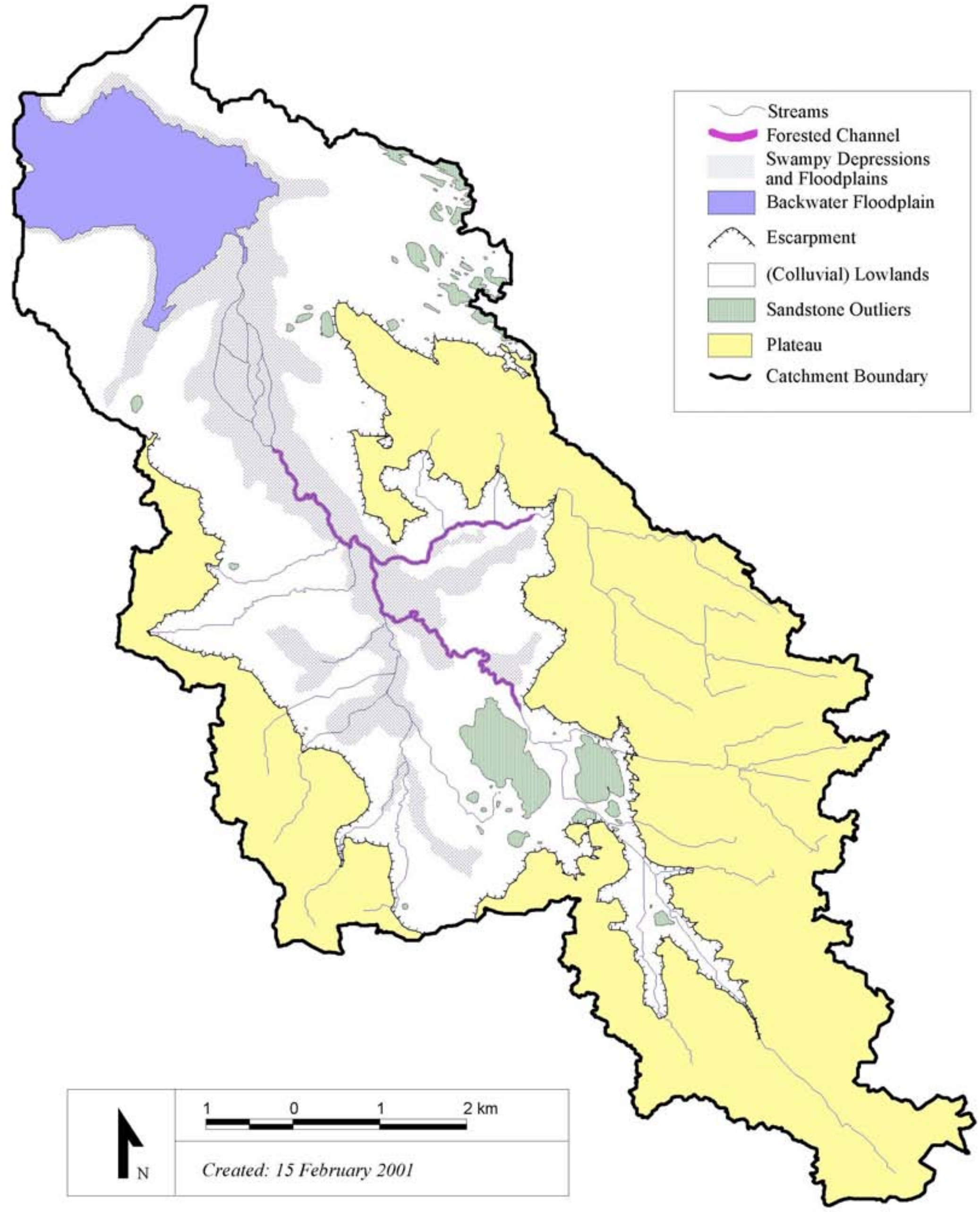

Figure 3 Preliminary geomorphic map of the Swift Creek catchment based on air photograph interpretation of the August 1991 1:10 000 prints

The Jabiluka mine site channels are discontinuous, unstable, ephemeral streams, which are not lined by riparian forest (section 6.3). These channels are similar to ephemeral streams in other climates and exhibit a series of cut and fill cycles over decadal time spans (Patton & Schumm 1981). Channel erosion occurs by knickpoint formation, upstream knickpoint retreat and subsequent bank erosion of the incised sections (Patton & Schumm 1981, Erskine & Melville 1983a, Melville & Erskine 1986). Gullied sections are separated by aggrading or stable sections (Patton & Schumm 1981, Erskine & Melville 1983a, Melville & Erskine 1986). Tributary North exhibits complex channel morphology, has had a diversion channel excavated through the mine site and is the outlet for seepage water from under the retention pond. There is an extensive gully network immediately upstream of the confluence with Swift Creek. The sand in Tributary North is redder in colour, due to iron staining, than the buff coloured sand in Swift Creek. A tributary mouth bar of this redder sand is usually present in Swift Creek immediately downstream of the junction.

6.3 Channel reach definition and mapping

All major channels in the Swift Creek catchment have been tentatively classified into geomorphologically homogeneous reaches. Kellerhals et al (1976) and Rosgen (1994, 1996), among others, have proposed schemes for channel reach characterisation. However, it must be stressed that there is no universally acceptable method and any classification will require modification to suit rivers different to those used to derive the scheme (Kondolf & Downs 1996). Different reaches are usually subject to different biogeomorphic processes and hence provide an appropriate spatial framework for field sampling and monitoring activities. Kondolf and Downs (1996) emphasise that, due to *equifinality*, it is not always possible to correctly infer the controlling factors for a particular channel type solely from its morphology, as attempted by some ecologically based classifications (Rosgen 1994, 1996). Nevertheless, the method is important for evaluating the significance of local factors in determining river stability/instability (Erskine 1992, 1993).

The preliminary classification of geomorphologically homogeneous channel reaches in the Swift Creek catchment is based on field work, aerial inspections, and map and air photograph interpretation. Channel reaches are named and defined in table 3 and those that can be clearly shown on the air photograph mosaic are included in figure 4. This classification is based on channel pattern, cross sectional morphology, bed profile and bedforms, confinement by materials of limited erodibility, channel bars, secondary channels, large woody debris and riparian vegetation (see section 6.14), floodplain development, channel incision, gullying, etc. Future work will revise and better characterise these reaches, as well as document any shifts in reach boundaries or characteristics over time.

Sediment movement through the Swift Creek channel network is characterised by many discontinuities because of active storage sites. Vegetated depressions, *Melaleuca* swamps, floodouts and terminal wetlands are significant mud storages while floodouts, fan deltas and floodplains are major sand storages. Integrated channels deliver sediment to large storages while discontinuous channels deliver sediment to small storages. The mine site tributaries do not have a fully integrated channel network with Swift Creek and hence will not immediately supply coarse sediment (sand) to the main stream. Melville and Erskine (1986) determined that 90% of the sandy valley-fill sediment eroded by historical discontinuous gullying in one 13 km^2 catchment in the Hunter Valley, NSW was still stored in the channel network as sandy floodplain and floodout deposits. Neil and Fogarty (1991) estimated that as much as 60% of the material eroded from discontinuous gullies in the Southern Tablelands of NSW was deposited in the downstream floodout. Sediment linkages between different channel reaches are often poor so that sediment storage will be the immediate response to increased sediment inputs, particularly for the sand fraction.

Only East Tributary has a fully integrated channel with Swift Creek. Tributary West deposits its sandy bedload in the *Melaleuca* Swamp Reach (table 3). Tributary South is a discontinuous channel and does not currently transport significant amounts of sand. Tributary Central exhibits a marked downstream decrease in channel capacity and stores large amounts of sand in the point bars of the Sinuous Reach and on the floodplain of the distal Small Capacity Reach (table 3). Additional sand is stored further downstream in the anabranch of Swift Creek. Tributary North stores the sand generated in the upper catchment in the Floodout Reach. However, the distal Gullied Reach is currently being eroded and is supplying sand to Swift Creek.

Table 3 Preliminary definition and characteristics of geomorphologically homogeneous channel reaches in the Swift Creek catchment. All reaches are arranged in downstream sequence for each stream. For location of most of the reaches on Swift Creek and East Tributary, see figure 4.

River	Reach name	Reach description
Swift Creek	Forested Bedrock-Confined Headwaters	Essentially straight sandstone gorge cut into the lower Kombolgie Formation. Channel follows a probable fault and is densely vegetated by riparian forest.
Swift Creek	Forested Straight Reach	Extensive area of dense riparian forest where the sand-bed channel is straighter but much less bedrock-confined than immediately upstream.
Swift Creek	Forested Meandering Reach	Long section of meandering, sand-bed channel continuously vegetated by riparian forest. Occasional bedrock bars and large woody debris in bed; continuous floodplain present.
Swift Creek	Anabranch Reach	Long section of meandering, sand-bed channel continuously vegetated by riparian forest. Large woody debris in channel. Long ill-defined anabranch on left bank floodplain. There is a mud- and then a sand-floored billabong at the upstream end of the anabranch. Tributaries West and South debouch into the upstream mud billabong and Tributary Central debouches into the anabranch. There is also a shallow mud billabong on the anabranch.
Swift Creek	Sinuous Reach	Sinuous, sand-bed channel with less dense riparian vegetation and a broad floodplain. Sand splays and eroded depressions are present on floodplain.
Swift Creek	Braided Floodout Reach	Multiple, ill-defined, often discontinuous, sand-bed channels separated by vegetated mud depressions which are often buried by linear sand splays. Locally wider section of floodplain. Significant sand storage zone.
Swift Creek	Fan Delta Reach	Short reach of active sand deposition by multiple diverging, sand-bed channels which debouche into terminal wetlands. Significant sand storage zone.
Swift Creek	Terminal Wetland Reach	Terminal wetlands of Swift Creek which are contiguous with Magela Creek wetlands. Significant mud storage zone.
Tributary West	Sandy Reach	Long reach of integrated, shallow, ecologically featureless, sand-bed stream with sand bars and marginal sandy benches.
Tributary West	*Melaleuca* Swamp Reach	Short reach of discontinuous sand-bed channels flowing through a *Melaleuca* forest. Small pools present at sites of local scour. Active sand storage zone.
Tributary South	Headwater *Melaleuca* Swamp Reach	Headwaters in a depression vegetated by *Melaleuca* forest and saturated during the Wet season. No integrated channel exists.
Tributary South	Cut and Fill Reach	Middle section of alternating gullies and swampy depressions. Knickpoints and their associated plunge pools are slowly eroding the intervening swampy depressions and generating sand and mudballs. Gullies are not currently extensive.
Tributary South	Grassed Depression Reach	Lower section of grassed, ill-defined depressions. No sand is currently being supplied to Swift Creek.
Tributary Central	Headwaters Reach	Steep, essentially bedrock channel cut into strongly ferruginised sandstone of the lower Kombolgie Formation.
Tributary Central	Bedrock-Confined Reach	Steep channel discontinuously vertically confined by ferruginised sandstone of the lower Kombolgie Formation.
Tributary Central	Sinuous Reach	Short section of sinuous channel with active cutbank erosion on the outside of bends and sandy point bars on the inside. Bedrock (ferruginised sandstone of the lower Kombolgie Formation) crops out in the bed.
Tributary Central	Large Capacity Reach	Relatively straight, large capacity, sand-bed stream with unstable sandy banks.

Table 3 cont….

River	Reach name	Reach description
Tributary Central	Small Capacity Reach	Downstream section of small capacity, sand-bed stream with anabranches. Large woody debris present. Active sand deposition on the floodplain.
Tributary North	Headwaters Reach	Steep, essentially bedrock channel cut into strongly ferruginised sandstone of the lower Kombolgie Formation.
Tributary North	Diverted Reach	Artificially excavated diversion channel through the Jabiluka mine site.
Tributary North	Floodout Reach	Sand deposits and depressions in the floodout of the upstream channel.
Tributary North	Gullied Reach	Recently gullied lower section of channel that is still extending headwards and is actively enlarging.
East Tributary	Uplands Reach	Joint-controlled channel on the Arnhem Land Plateau.
East Tributary	Bedrock Falls Reach	Steep bedrock channel cut in sandstone along joint systems in the lower Kombolgie Formation where East Tributary descends over the Arnhem Land Escarpment.
East Tributary	Plunge Pool Reach	Deep plunge pool and associated large sand bar at the base of the Bedrock Falls Reach.
East Tributary	Sandy Straight Reach	Short length of relatively straight, sand-bed channel which is not well protected by riparian vegetation.
East Tributary	Forested Meandering Reach	Long section of meandering, sand-bed channel continuously vegetated by riparian forest. Large woody debris common in bed

The morphology of Swift Creek changes markedly downstream from well vegetated, stable channels (upstream four reaches in table 3) to active downstream depositional zones (downstream three reaches in table 3) with only a relatively short transition zone (Sinuous Reach in table 3 and fig 4). Figures 5, 6 and 7 show three of the upstream reaches, which are all stable and well vegetated. The lower section of Swift Creek is a significant long term sediment storage zone not only for the sediment transported by Swift Creek but also by many of the tributaries (East Tributary, Tributary North and Tributary Central). Upstream of the Oenpelli Road is a large area of discontinuous braided sand channels (Braided Floodout Reach) (fig 8) and downstream of the Oenpelli Road is a large sandy fan delta (Fan Delta Reach) (fig 9). Extensive terminal wetlands extend for about 3 km between the fan delta and the Magela Creek wetlands (Terminal Wetland Reach). No sand has reached Magela Creek from Swift Creek since sea level approached its present level about 6.8 ka BP (Woodroffe et al 1987, Clark et al 1992). The Braided Floodout Reach and Fan Delta Reach are the long-term stores for sand currently being transported by Swift Creek. Suspended sediment (ie mud) is stored in the wetlands downstream of the fan delta but upstream of Magela Creek (fig 10). A similar situation occurs on the much larger Magela Creek upstream of the East Alligator River (Hart et al 1987, Cull et al 1992, Murray et al 1993, Erskine & Saynor 2000).

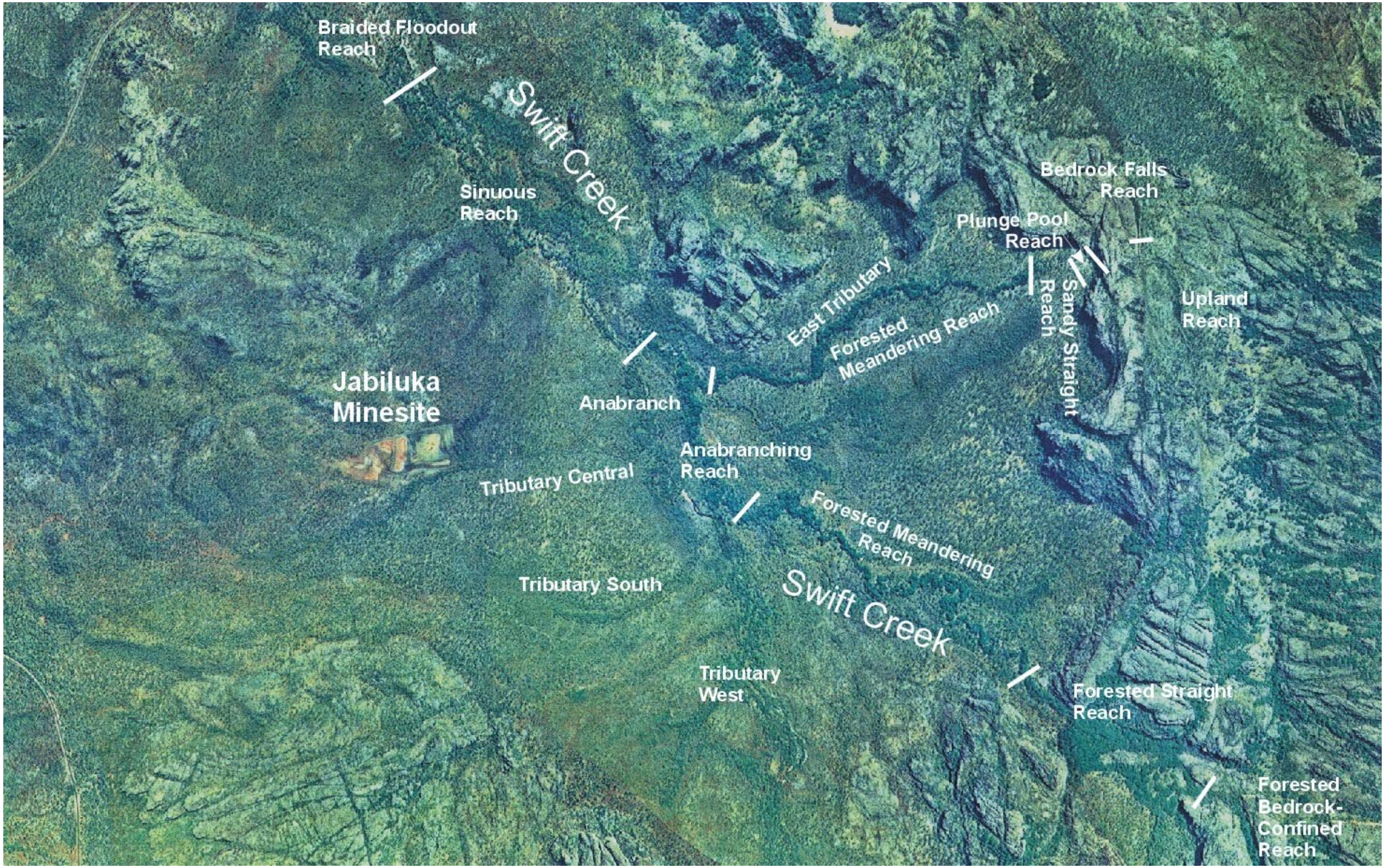

Figure 4 Geomorphologically homogeneous channel reaches in part of the Swift Creek catchment. The reaches on Tributary North, Tributary Central, Tributary South and Tributary West are not shown because they are too short to be clearly depicted at the photo scale.

Figure 5 Upstream view of Forested Bedrock-Confined Headwaters Reach of Swift Creek showing dense riparian vegetation growing in fault-controlled, straight sandstone gorge (17 June 1999)

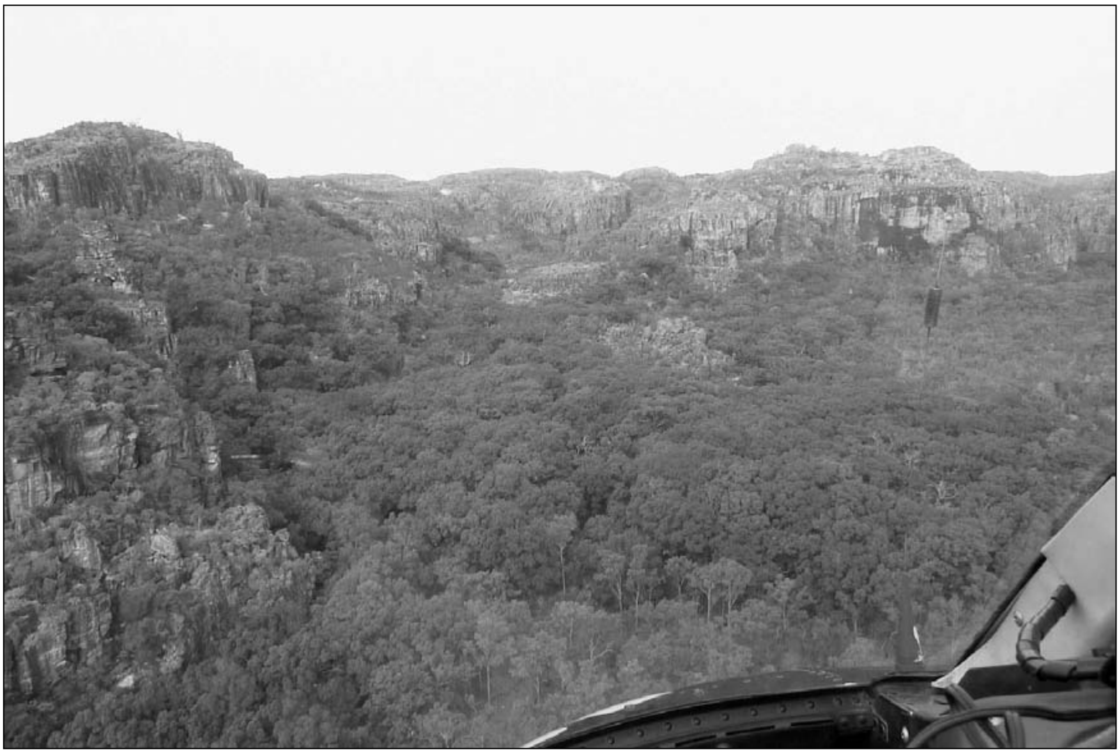

Figure 6 Upstream view of Forested Straight Reach of Swift Creek showing dense riparian vegetation growing where channel debouches from sandstone-confined valley (17 June 1999)

Figure 7 Upstream view of Forested Meandering Reach of Swift Creek showing meandering channel pattern and dense riparian vegetation (9 September 1998)

Figure 8 Downstream view of Braided Floodout Reach on Swift Creek upstream of the Oenpelli Road (9 September 1998)

Figure 9 Downstream view of Fan Delta Reach on Swift Creek downstream of the Oenpelli Road (9 September 1998)

Figure 10 Upstream view of Terminal Wetland Reach on the lower section of Swift Creek (9 September 1998)

6.4 Recent channel stability/instability

The historical stability/instability of the mine site tributaries (Tributaries North, Central and South) and Swift Creek should be determined from all available vertical air photographs to provide an understanding of pre-mining channel behaviour and to provide baseline conditions for the assessment of post-mining channel changes. While many different data sources have been used to reconstruct historical channel changes on Australian rivers (for examples, see Erskine 1986a, 1986b, 1992, 1993, 1999, Melville & Erskine 1986, Erskine & White 1996), most of these sources (except for vertical air photographs) do not exist for the Swift Creek catchment. Therefore, vertical air photographs in combination with field evidence must be used to determine channel changes over the last 50 years. In particular, the location and type of channel change, erosion, anabranch development and avulsions, and sediment storage zones need to be identified. The riparian forest present on Swift Creek upstream of the East Tributary junction greatly restricts visibility of the channel on the photographs. Therefore, a person with detailed local knowledge of the channel network must carry out the photogrammetric work.

This project involves the collection of all available air photographs of the Swift Creek catchment (see table 1 and accompanying text). A geomorphologist/photogrammetrist should map changes in channel conditions, erosion and deposition over time. Detailed analysis of the changes should provide important information on channel behaviour, erosion and deposition before mining. This will enable an assessment of the impact of mining on channel processes and sediment movement. Air photographs were not available when this report was compiled so a preliminary assessment of recent channel stability/instability could not be undertaken.

6.5 Channel and floodplain sediments

6.5.1 Field methods

The cross sections discussed below (section 6.12) should be used to systematically sample channel bed and bank, and floodplain sediments. Because these sites will be used to measure sediment storage throughout the channel network, the nature of the sediments themselves should also be determined (Reid & Dunne 1996). These sections sample the sediment source zones, sediment transfer zones and sediment storage zones of Schumm (1977).

Bulk samples of channel bed and bank sediments are the usual method of sampling fluvial sediments. This involves the collection of all material from a predetermined volume within a specific geomorphic environment (Kellerhals & Bray 1971). Such samples are then air dried (40°C) and subjected to relevant laboratory analyses. In terms of grain size analysis, bulk sieve analysis has been recommended as the standard for use with river sediments (Kellerhals & Bray 1971). Bulk samples should be collected of soil, sand, fine gravel and mixed sand and fine gravel by spade or hand trowel to a depth of 0.05 m at multiple sites on each surveyed cross section. At least 5 equally spaced points on the river bed of each cross section should be combined for a single bed sample. Although no gravel-bed sites were found during field inspections, they may be present near sandstone outcrops. Gravels should be sampled by the grid-by-number technique of Wolman (1954), using the Leopold (1970) modification for field sampling. This method is recommended because the masses required to representatively bulk sample large gravels are extremely large (see following discussion). Bank sediments should be collected at 0.25, 0.5 and 0.75 the height of each bank up to the floodplain or the main valley flat level and bulked, following the method of Pickup (1976).

Floodplain sediment samples are more difficult and time-consuming to obtain. Sand augers and/or the ***eriss*** rotary auger drill rig should be used for this purpose on the surveyed cross sections. Sand augers are essential because of the sandy texture of all the sediments. Rotary auger drill rigs do not provide detailed sediment depth profiles because of mixing but are much quicker for accessible sites.

Very large sample masses are required to obtain reproducible measures of the grain size distributions of samples containing individual large clasts (de Vries 1971, Church et al 1987, Gale & Hoare 1992, Ferguson & Paola 1997). Small sample masses are only required if a specific percentile is desired that is *not* in the coarse tail of the grain size distribution (Ferguson & Paola 1997). Minimum sample mass also depends on sediment sorting or the dispersion of the grain size distribution (Gale & Hoare 1994, Ferguson & Paola 1997). For a particular geomorphic environment, poorly sorted sediments, such as found in mixed sand and gravel bed rivers, require larger samples than better sorted sand samples (Gale & Hoare 1994, Ferguson & Paola 1997). According to the Church et al (1987) relationship for modern fluvial gravels, a sample mass of 1 kg is adequate to obtain reproducible measures of the grain size distribution for sediments with a maximum size of about 9.5 mm. According to de Vries (1971), 'high accuracy' definition of a 16 th percentile of 1 mm requires a mass of 200 g. 'Normal accuracy' requires a mass of only 20 g. In the Swift Creek catchment, most bed material contained only a small gravel fraction that was usually less than 10 mm in b axis diameter. Therefore, bulk samples of about 1 kg mass should be sufficient to reliably determine the full grain size distribution of fluvial sediment samples. Bulk sampling is usually restricted to small areas that may not be representative of all of a specific geomorphic environment (Wolman 1954, Muir 1969). This is a major concern on large rivers with spatially variable geomorphic environments (Mosley & Tindale 1985) but is not a problem on the small channels in the Swift Creek catchment.

6.5.2 Laboratory methods

All bulk sediment samples should be air dried at 40°C before being subjected to grain size analysis. The gravel fraction of all samples should be either manually or automatically (15 minutes shake time) sieved in their entirety at $\phi/2$ intervals. The sand fraction should be either coned and quartered, or passed through a riffle box, until an approximately 50 g sub-sample (or whatever mass will not damage analytical grade sieves) is obtained. This sub-sample should then be dry sieved through a nest of sieves at $\phi/2$ intervals using a 15 minute shake time. The phi (ϕ) notation system is often used to describe the grain size of clastic sediment by sedimentologists. It is a logarithmic scale in which each grade limit is twice as large as the next smaller grade limit (Folk 1974). Phi (ϕ) is formally defined as:

$$\phi = -\log_2 d \qquad (1)$$

where d is the grain diameter in mm.

The Wentworth grain size terminology for sediments is based on the phi scale and is used throughout this report (table 4). Some bed sediments in Tributary North and in Swift Creek immediately downstream contained observable quantities of mud (ie <0.063 mm in diameter). Such samples should be wet sieved to ensure that the whole mud fraction is accurately measured, especially as contaminants are usually transported adsorbed to the fine-grained sediments (Erskine & Saynor 1996b).

The fine earth fraction (ie <2 mm fraction) of samples containing a significant mud fraction should be chemically dispersed with 25 mL of sodium hexametaphosphate or equivalent before being mechanically dispersed on a shaking wheel or a shaking platform for at least 12 hours. The sample then should be wet sieved through a 0.063 mm or 4 ϕ stainless steel sieve and the sand fraction should be oven dried, weighed and dry sieved through a nest of sieves at $\phi/2$ intervals, as outlined above. The mud suspension should be transferred to a 1000 mL cylinder, made up to volume and left in a constant temperature room for at least 24 hours to allow temperature equilibration. An ASTM 152H hydrometer, a pipette or an auto size analyzer should be used to determine the grain size distribution of the mud suspension (ie the amount of silt and clay). The ASTM 152H hydrometer is the one used for the derivation of most sediment settling equations for the hydrometer method (Gee & Bauder 1986). The fraction coarser than 0.02 mm or 5.65 ϕ should be also determined by decantation using a sedimentation time based on Stokes equation for the water temperature at the time.

Table 4 The Wentworth grain size scale for sediments (after Folk 1974)

Lower Class Boundary (mm)	Lower Class Boundary (ϕ)	Wentworth Size Class
256	-8	Boulder
64	-6	Cobble
4	-2	Pebble
2	-1	Granule
1.00	0	Very coarse sand
0.50	1	Coarse sand
0.25	2	Medium sand
0.125	3	Fine sand
0.0625	4	Very fine sand
0.031	5	Coarse silt
0.0156	6	Medium silt
0.0078	7	Fine silt
0.0039	8	Very fine silt
0.00006	14	Clay

It may be necessary to determine other characteristics of the channel boundary and floodplain sediments besides grain size and so all of the non-analysed portion of the collected samples should be stored safely for possible subsequent analyses.

6.6 Digital elevation model

DEMs are rectangular grids of evenly spaced terrain heights that can be generated from either spot height data, contour data, scanned aerial photographs or satellite images. A DEM has been generated for the Swift Creek catchment (fig 11). The geographic coverage of the DEM includes the entire Swift Creek catchment, extending from slightly upstream of the confluence of the Swift Creek backwater plain with the Magela Creek floodplain to the headwaters of the creek in the Arnhem Land plateau. The majority of the DEM has been captured from the stereo photogrammetric interpretation of 1:25 000 pre-mining (1991) aerial photography. However, the area surrounding the Jabiluka outlier has been interpreted from 1:30 000 aerial photography captured in 1997. The final DEM was produced on a 5 m grid and has a relative vertical accuracy of ± 0.5 m and relative horizontal accuracy of ± 2 m (fig 11). Such a DEM does not have sufficient spatial resolution to detect channel changes.

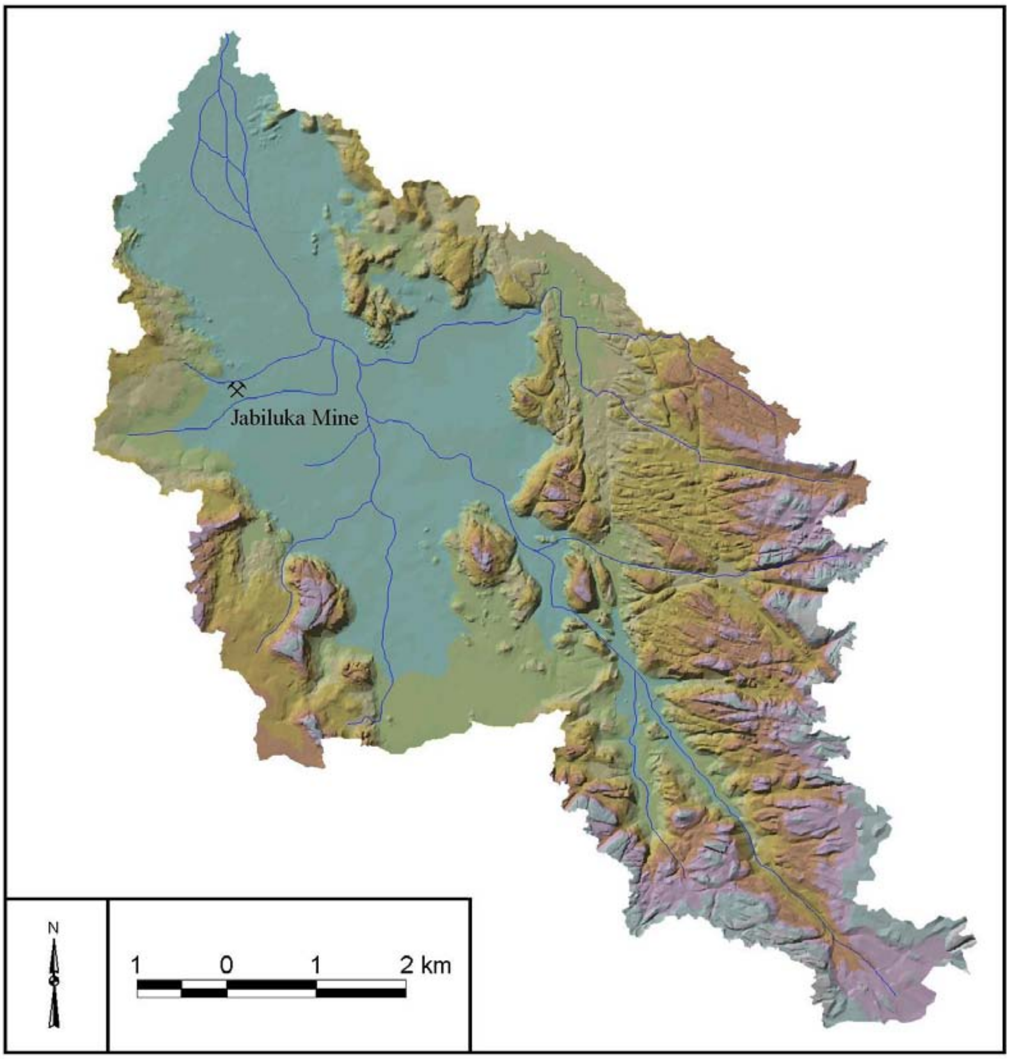

Figure 11 DEM of Swift Creek catchment

This DEM will be used in collaborative research with Northern Territory University and University of Newcastle to develop a GIS-based catchment management modelling technology using existing erosion, hydrology and landform evolution models. Mine site rehabilitation research at ***eriss*** has previously focused on the application of a landform evolution model, SIBERIA (Evans et al 1998, Willgoose & Riley 1998) to post-mining rehabilitated landform design at Ranger. The main results of this work are presented in Evans et al (1998) and Willgoose and Riley (1998). SIBERIA is a sophisticated DEM-based 3-dimensional topographic evolution model simulating runoff, erosion and deposition. It predicts the long-term evolution of channels and hillslopes in a catchment. The location and rate of development of gullies are controlled by a channel initiation function that is related to runoff and soil erodibility (Willgoose et al 1989). The model solves for two variables; elevation, from which slope geometry is determined, and an indicator function that determines where channels exist. In this way, the evolving drainage system of a catchment can be modelled. Channel growth is regulated by an activation threshold, which depends on discharge and slope gradient. A surface may commence with no gullies but when the activation threshold is exceeded, a channel is eroded. The model has continued to be enhanced by Willgoose and co-workers (eg Moglen & Bras 1994). Derivation of SIBERIA input parameters requires input from an erosion model and hydrology model calibrated to site-specific conditions (Evans 1997). Much data have been collected for the ERA Ranger mine and the model has been parameterised successfully (Evans et al 1998, Willgoose & Riley 1998). The research is now moving toward extending the application of SIBERA from the mine site to the total catchment and developing it as a proactive catchment management tool. The aim is to calibrate SIBERIA to the Swift Creek catchment using sediment transport, hydrology and digital elevation data and predict how the catchment will evolve for various scenarios of mine site development at Jabiluka. Model outputs could be used for early management of any indicated adverse impacts. It is anticipated that this technology will have broad application to management of catchment impacts (Boggs et al 1999).

6.7 River gauging stations

The aims of this project include providing baseline data on the hydrology and sediment transport of the channels in the Swift Creek catchment as well as determining the impacts of uranium mining. To do this, it is essential that continuous streamflow data are obtained at a number of sites upstream and downstream of the mine site. ERA is currently gauging the neighbouring 7J and North Magela Creeks. Sediment loads can only be calculated if there are corresponding accurate discharge data. During the field inspections, potential gauging and sediment transport measurement sites were identified on Swift Creek, East Tributary and Tributary Central at the mine site (fig 1). Two sites were selected on Swift Creek, namely the existing ERA site below the Tributary North junction and an upstream site above Tributary West. The Tributary Central and downstream Swift Creek sites are intended to measure the impact of the mine while the East Tributary and upstream Swift Creek (Upper Main) sites are intended to measure natural catchments which have not been impacted by mining.

It is not possible to locate a gauging station on Swift Creek between the Tributary West and Tributary North confluence for the following reasons:

- There is a long, ill-defined anabranch paralleling Swift Creek which receives flow from a number of tributaries, as outlined below.
- Tributary West and Tributary South debouche into the mud billabong at the upstream end of the Swift Creek anabranch.
- Tributary Central debouches into the Swift Creek anabranch.
- The shallow, vegetated nature of the anabranch is difficult and dangerous (crocodiles) to gauge during the Wet season and is difficult to rate and hence would produce less reliable discharges.

Two gauging stations would be required to measure flow here, one on the main channel and one on the anabranch. This option was too expensive and involved too much Wet season field and laboratory work. Furthermore, a gauging station could not be located on Tributary West because an appropriate site could not be found on the lower 5 km of channel. The *Melaleuca* Swamp Reach has no well-defined channel and hence no suitable channel control to establish a stable and reliable stage-discharge relationship. The length of the Sandy Reach inspected was characterised by a wide, shallow sand-bed stream flanked by a floodplain or benches. There was also no suitable stable channel control and any rating curve would be unreliable for sub-bankfull flows. Therefore, the well defined, vegetated, stable channels in the Forested Meandering Reaches of Swift Creek and East Tributary were selected as control sites for the two mine-impacted sites. Data from these control sites can be supplemented by that for 7J and North Magela Creeks, at least until the location of the mine access road is determined.

While control structures, such as flumes or weirs, would be desirable, the associated construction would cause much disturbance of the channel and the riparian zone in, or next to, the World Heritage Listed Kakadu National Park. Because existing ERA stations on Swift Creek, 7J Creek and North Magela Creek all operate effectively without control structures, it is recommended that natural channel controls be adopted, except on the mine site tributaries, where weirs were built by ERA. Natural channel controls will result in reduced low flow sensitivity, which should only be an issue for a very short time (immediate beginning and end) in comparison to the rest of the Wet season.

Each site should be fitted with a float well, water level instrument with optical shaft encoder, data logger, a water level pressure transducer, turbidity meter, pump water sampler, pH and electrical conductivity probes, solar panels, staff gauges, boat, wire cable across the channel (ie not a cableway) and bench mark.

Pulleys on the float can slip and so the pressure transducers are recommended as the primary height sensor with the optical shaft encoder as the backup. Pluviometers should also be installed at each site to measure rainfall depth, timing and intensity.

Because sediment transport measurements will also be undertaken at each site, straight reaches without strong secondary currents and reverse currents have been deliberately selected for gauging sections. A gauging section for all velocity-area gaugings has been selected at each station (the cable section). The gaugings will be used to construct rating curves at each station. All gaugings should be conducted at the same site as the bedload measurements so that site-specific hydraulic parameters can be derived.

6.8 Suspended sediment loads

Suspended sediment samples should be obtained as often as possible at the cable section at each river gauging station with the depth-integrated sampler USDH 48 (Guy & Norman 1970). This sampler collects the water-sediment mixture at a rate proportional to the flow velocity at various levels in the vertical and the resultant concentration represents a discharge-weighted mean concentration for that vertical (Gregory & Walling 1973). A USDH 48 sampler is designed so that it will not collect bed material when it reaches the bed. There is an unsampled zone of about 0.1 m immediately above the bed. Nevertheless, all field work needs to be conducted carefully to ensure that bed sediment is not inadvertently sampled.

Depth integrated suspended sediment sampling is conducted according to either the Equal Transit Rate method or the Equal Discharge Increment method (Guy & Norman 1970). The *Equal Transit Rate* method is recommended and involves moving the sampler at a constant rate between the water surface and the bed at each of a series of verticals equally spaced across the channel. No prior knowledge of the velocity pattern is required at the sampling site to obtain a mean suspended sediment concentration for the whole section. The *Equal Discharge Increment* method involves dividing the cross section up into a series of segments of equal discharge and collecting depth integrated samples at the centroid of each segment. Clearly, the latter method can only be used when a complete velocity-area gauging has also been completed and calculated.

Because of limited access during the Wet season, a stage activated pump-sampler should also been installed to obtain detailed time series variations in suspended sediment concentrations required for accurate load determinations (Rieger & Olive 1988). The sampler intake should be set about 0.2 m above bed level so that it samples suspended sediment and not small scale migrating sandy bedforms. Two pump-samplers could be installed at each gauging station to ensure that each flood event is adequately sampled and the storage capacity of the sampler is not exceeded between site visits. The sampling interval of each flood event should be programmed on stage following a trial and error procedure to determine the most efficient sampling strategy. More samples should be collected on the rising stage of the hydrograph than on the recession. The reason for this is that suspended sediment concentration in the Alligator Rivers Region often peaks before the hydrograph and sediment exhaustion occurs rapidly (Duggan 1988).

A number of simultaneous pump and depth integrated samples should be obtained to determine if the pump sample suspended sediment concentrations can be converted to equivalence with depth integrated samples. If two pump samplers are installed, they need to be activated so that they sample sequentially.

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 ERA Ranger Mine waste rock dump. He found that although some of the relationships were statistically significant they were associated with relatively large errors. This suggests that there are problems in using turbidity for continuous monitoring of suspended sediment transport in the Alligator Rivers Region. Further work is required along the lines of Gippel (1989a, 1989b, 1994) to resolve this issue. Continuous recording turbidity meters should be installed at each gauging station and detailed turbidity time series should be collected at 6 minute intervals. Turbidity is an important water quality parameter in its own right and, therefore, should be measured. Furthermore, the relationship between turbidity and suspended sediment concentration should also be investigated further to determine whether turbidity can replace suspended sediment monitoring. The turbidity probes (Greenspan TS 100) should be installed at least 0.2 m above the bed and should be shaded by a hood with a black inner lining, following manufacturer's recommendations.

All suspended sediment samples should be analysed for pH, electrical conductivity and turbidity before being wet sieved through a 0.063 mm sieve to determine the suspended sand concentration. The mud concentration (<0.063 mm) in the remainder of the sample should then be determined by filtration through a cellulose nitrate filter paper (0.45 µm diameter). This is a very time consuming process that is not very accurate for low concentrations (LJ Olive 1996, pers comm). It also enables the solute concentration to be determined on the filtrate. The combined solute and mud concentrations have also been determined on the filtrate at ***eriss*** (Evans 1997) and this practice is more time efficient.

Hysteresis plots of suspended solids concentration versus instantaneous discharge for all events should be plotted to determine the complexity and range of response patterns in this environment and whether they are effected by mining (Olive & Rieger 1985, 1987). In the seasonally wet tropics, the multiple rise patterns of Olive and Rieger (1987) are most relevant and are likely to be very complex (Olive & Rieger 1987). This work is necessary to provide important information on suspended sediment transport processes and on the most accurate methods of load estimation. The range of load estimation procedures outlined by Letcher et al (1999) should be evaluated to determine the most accurate method.

Suspended sediment transport in Australian rivers is usually storm dominated (Erskine & Saynor 1996a, 1996b, 2000). Duggan (1988) found that suspended sediment concentration in natural catchments of the Alligator Rivers Region was best correlated with peak discharge and that suspended sediment transport was dominated by infrequent, large events. The seasonal distribution of suspended sediment transport was dominated by large discharges that occurred most frequently in February and March. Duggan (1988, 121) also concluded that rare events could be expected to transport disproportionately high loads of suspended sediment. Extreme rainfall events will cause extreme rates of soil loss and, therefore, it is essential that detailed information be obtained on catastrophic events. The Extreme Events Project recommended by Erskine and Saynor (2000) for the Ranger mine should be undertaken because such information is also required for an understanding of suspended sediment dynamics and for the design of a stable rehabilitated mine site at Jabiluka.

Water quality impacts of uranium mining are also important and are being addressed by the Biological Monitoring/Environmental Chemistry section of ***eriss***. This program is not discussed here.

6.9 Bed-material loads

The Helley Smith pressure difference bedload sampler (Helley & Smith 1971) was designed by the United States Geological Survey, Water Resources Division to be compatible with depth integrated suspended sediment samplers and is one of the most accurate bedload samplers yet designed (Emmett 1979). The orifice diameter of the Helley Smith sampler closely approximates the unsampled zone between the intake nozzle and the bed of a depth integrated suspended sediment sampler (Helley & Smith 1971). The Helley Smith sampler should be used on Swift Creek and was also used by Roberts (1991) on the neighbouring Magela Creek.

Field methods should follow those used by the United States Geological Survey, as outlined by Carey (1984, 1985), among others. These methods are more rigorous than those used by Roberts (1991) who conducted 'quick' field measurements. Basically, at least four point measurements of bedload transport should be taken at the wire cross section at each gauging station. Point measurements are weighted by the bed width for the zone of bedload transport for which they are representative. The bag on the pressure difference sampler must *not* be filled when sampling because it alters the sediment trap efficiency of the sampler (Emmett 1979). Measurement times should be determined on a trial and error basis so that no more than about one-third of the bag is filled. Each bedload gauging should consist of a double pass across each section (ie at least eight point measurements) and then should be combined as a single sample. Although instantaneous bedload fluxes are highly variable, it is usually possible to define a mean flux for a given discharge, provided thorough field measurements are made (Carey 1985). All bedload samples should be bagged in the field and dried and weighed in the laboratory. These samples should also be used for grain size analysis for comparison with the bulk bed-material samples (section 6.5).

Details of small and large-scale bedforms should be noted, whenever possible, during the bedload gaugings to investigate changes in bedload flux with bedform. Small-scale bedforms in sandy sediment have been outlined by Simons et al (1965), Simons and Richardson (1966) and Allen (1985), among others. These schemes should be followed whenever possible.

Load estimates will have to be made from the infrequent bed-material load gaugings. This will entail the evaluation of a range of methods to determine those most accurate for this environment. The relationships between sand flux and various hydraulic parameters will have to be explored. The simplest method is to derive a statistically robust relationship between sand flux and discharge, and then use the relationship to calculate sand loads for other discharges.

Catastrophic floods cause large-scale bank erosion that often overload channels with sand and substantially aggrade the bed (Erskine 1986b, 1994, 1996, 1999, Erskine & Melville 1983b, Erskine & Saynor 1996a, Erskine & Livingstone 1999). For this reason, it is essential to compile all information on these extreme events. The Extreme Events Project recommended by Erskine and Saynor (2000) for the Ranger mine should be undertaken because such information is also required for an understanding of bed load fluxes and for the design of a stable rehabilitated mine site at Jabiluka.

6.10 Bed scour depths

Each Wet season, the bed material of Swift Creek and its tributaries is reworked and transported downstream at various rates to various sediment storages, such as the channel bed, various types of channel bars, floodouts, the braided reach above the Oenpelli Road and the fan delta below the Oenpelli Road. While the bed-material fluxes will be measured at the gauging stations (see section 6.9), it is also important to know the depth to which the bed is scoured each Wet season. The channel bed will be one of the first temporary stores to receive sediment generated on the mine site. Therefore, the depth of active bedload transport should be determined at each gauging station and at various sites on the mine site tributaries (this only applies to sand-bedded Tributaries North and Central).

Scour chains (heavy interlocked metal or plastic chains placed vertically into the bed sediment during the Dry season) are the best means of measuring scour depths (Leopold et al 1966). Chains should be installed before the onset of the Wet season when it is possible to excavate a 1 m deep pit into the sandy bed material. ERA hydrographers found up to 0.2 m of bed scour and a maximum mean flow velocity of about 1 m/s during the 1997/98 Wet season at their gauging section on Swift Creek. Therefore, a 1 m chain length was thought to be sufficient to measure Wet season scour depth. The linked vertical chain will lie on the scoured-bed surface as bed level deepens. It will be buried as the bed fills at the end of the Wet season. The location of each chain on each sampled cross section must be accurately determined and the whole cross section surveyed before chains are re-excavated after the Wet season. A metal detector will assist in the relocation of scour chains.

It is recommended that:

- at least five scour chains should be installed at three cross sections at the East Tributary gauging station;
- at least six scour chains should be installed at three cross sections at the Swift Creek gauging station;
- at least six scour chains should be installed at three cross sections at the upper gauging station on Swift Creek;
- at least seven scour chains should be installed on Tributary North; and
- at least three scour chains should be installed on Tributary Central.

6.11 Channel erosion rates

Field inspections indicated that the dominant channel erosion processes in the Swift Creek catchment were:

1 Erosion of the outside (concave) bank on bends, which is common in the sinuous reach of Tributary Central (table 3);

2 Upstream migration of the primary knickpoint at the head of a gully, which is currently occurring at the upstream end of the gullied reach on Tributary North (table 3);

3 Channel widening subsequent to gully incision by the primary knickpoint (gullied reach of Tributary North);

4 Bed degradation in the lower gully by the upstream migration of secondary knickpoints downstream of the gully head (gullied reach of Tributary North);

5 Development of anabranches, such as in the anabranch reach of Swift Creek (table 3); and

6 Erosion of flow-aligned scour pools, similar to those described by Scott and Erskine (1994) on alluvial fans in sandstone catchments (floodout reach of Tributary North).

The first four processes are the most widespread. A rapidly expanding literature has demonstrated that channel sources are an important and often the dominant sediment source on many Australian rivers (Erskine & Melville 1983a, 1983b, Melville & Erskine 1986, Erskine 1992, 1994, 1996, 1999, Erskine et al 1990, Erskine & Saynor 1996a, 1996b, Wasson et al 1996). To determine the significance of channel erosion as a sediment source in the Swift Creek catchment, measurements of bank erosion and knickpoint migration rates at appropriate sites should be made during the Wet season. The mine site tributaries and Swift Creek should be investigated in detail. The cross sections recommended for determining channel sediment storage (see section 6.12) are capable of measuring large-scale bank erosion only (Wolman 1959). Erosion pins are needed to measure relatively slow rates of bank retreat (Wolman 1959, Erskine et al 1995).

Erosion pins, metal rods painted white of about 10 mm diameter, 300 mm length, should be installed on vertical bank sections at a spacing of about 0.3 m. About 10 mm of the pin should be left exposed so that they could be easily seen (Erskine et al 1995). The amount of exposure of each pin should be measured during each Dry season and then reset with the same amount of exposure before the next Wet season. This method is appropriate for measuring erosion by processes 1 to 3 outlined above. Cross sections and long profiles are better for measuring erosion by processes 4 and 6. The rate of anabranch formation is usually quite slow, ranging from 10^2 to 10^3 years (Erskine et al 1990, Schumm et al 1996) and should be determined from sequential vertical air photography.

It is recommended that:

- at least 20 erosion pins should be installed on six verticals at the East Tributary gauging station;
- at least 16 pins should be installed on four verticals at the Swift Creek gauging station;
- at least 28 pins should be installed on six verticals at the upper gauging station on Swift Creek;
- at least 40 pins should be installed on 12 verticals on Tributary North; and
- at least 45 pins should be installed on 10 verticals on Tributary Central.

To calculate the total amount of channel erosion it will be necessary to measure the length of channel affected by the various erosion processes by dGPS or air photograph interpretation. This will be done as part of the geomorphic mapping (section 6.2).

Each sediment layer at the main erosion sites should be described according to the methodologies recommended by McDonald and Isbell (1990), bulk sampled and subjected to various laboratory tests to evaluate sediment erodibility. Erskine et al (1995) found that grain size analysis, the Emerson (1967) aggregate stability test and the pinhole dispersion test (Sherard et al 1976) were necessary to discriminate between stable and unstable bank materials. Generally sandy and/or silty materials are more erodible than other textures and sediments that lose coherence on wetting are more erodible than those that do not. Grain size analysis measures the proportion of various size fractions present in a sample, whereas the Emerson and pinhole dispersion tests measure the coherence of sediment to wetting and to a water jet, respectively. It may be necessary to use alternative laboratory tests for erodibility, depending on the materials present.

6.12 Channel sediment storage

To determine contemporary channel stability/instability and whether sediment is deposited in, or eroded from, the channel bed, a series of permanently marked cross sections should be installed and repeatedly surveyed every Dry season. The cross sections should be located throughout the channel network of the mine site tributaries but concentrated in study reaches at the gauging stations on the other channels. An understanding of channel sediment storage in the reaches being used for sediment transport measurements (sections 6.8 and 6.9) is essential to assess sediment supply. At selected sites, surveyed longitudinal profiles should also been established over short channel lengths.

These cross sections and long profiles should be marked for the duration of the project using a star picket driven into the ground with the top 0.3 m encased with a circular concrete collar (plinth) at each end of the cross section. A coach bolt should be set into the concrete to provide an accurate bench mark. The location of all of the concrete plinths should then be determined using dGPS. Each cross section should be surveyed using a Topcon total station theodolite and stored in the GIS.

It is recommended that:

- at least six cross sections should be installed at each gauging station; and
- at least 12 cross sections should be installed on both Tributary North and Tributary Central.

For the initial baseline survey, auger holes should be dug at selected cross sections to provide stratigraphic information. Depth of sand in the channel bed should be determined by probe or sand auger, and should then be used to determine volumes of stored sand. The soil material should be described according to the methodologies recommended by McDonald and Isbell (1990). All sediments sampled should be described according to the textural classes of Folk (1974) and selected samples should be subjected to particle size analysis according to the methods of Gee and Bauder (1986). Other characteristics such as bulk density, soil moisture content, clay mineralogy and heavy mineral analysis of the sand fraction should also be determined. Samples should also be obtained from the spoil areas and other areas of the catchment to help define sediment sources. These data provide information on the sedimentary characteristics of the cross sections located throughout the catchment.

6.13 Sediment storages

There are specific sediment stores downstream of the mine site that can be mapped individually by dGPS. These sites, along with the channel bed, are likely to be the first areas to receive sediment eroded from the mine site. In particular, there are *six* well defined sediment storages that should be investigated. Firstly, the discontinuous channels on Tributary North immediately below the mine site terminate in intersection point deposits that should be mapped and sampled. Secondly, the lower gully on Tributary North contains a sinuous reach with well developed bends that have point bars on the inside bank. These bars should also be mapped and sampled. Thirdly, Tributary Central below the mine site contains the sinuous reach with large point bars. These bars should also be mapped and sampled. Fourthly, channel capacity decreases downstream on Tributary Central to such an extent that anabranches and sand splays are common on the floodplain (small capacity reach). These anabranches and splays should be mapped and their sediments sampled. Fifthly, Tributary Central debouches into a floodplain anabranch of Swift Creek and deposits its entire sandy bed load. These sediments should also be mapped and sampled. Lastly, there are numerous sand splays on the Swift Creek floodplain downstream of Tributary Central. The floodplain seems to be formed by the process of vertical accretion or overbank deposition (Wolman & Leopold 1957) because there is little bank erosion and lateral migration due to the stabilising effects of the riparian forest and large woody debris (see section 6.14). Furthermore, sand splays are very common. Therefore, the floodplain has been a long term sediment store and is likely to continue to store sediment in the foreseeable future.

6.14 Role of riparian vegetation and large woody debris in determining channel and floodplain stability

Vegetation is an important control on channel and floodplain stability. Hickin (1984) maintained that vegetation exerts a significant control on fluvial processes and channel morphology through the following five mechanisms:

1 Flow resistance

2 Bank strength

3 Bar sedimentation

4 Formation of log jams

5 Concave bench deposition.

However, channel contraction (Sherrard & Erskine 1991, Friedman et al 1996), bed stabilisation by log steps (Marston 1982, Erskine 1986a) and pool formation (Lisle 1986, Robison & Beschta 1990, Thompson 1995, Montgomery et al 1995) should be added to this list. Zimmerman et al (1967) concluded that vegetation was particularly effective in increasing the shear strength of banks on small channels. Smith (1976) found that bank sediment with 16–18% by volume of roots with a 50 mm thick root mat had '20 000 times' more resistance to erosion than comparable bank sediment without vegetation. Nanson et al (1993) concluded that riparian vegetation was an important stabilizer of sandy banks on Magela Creek in the anastomosing zone upstream of Mudginberri Billabong.

Coarse or large woody debris (LWD) is conventionally defined as woody material larger than 0.1 or 0.2 m in diameter and 1.0 m in length (Keller & Swanson 1979, Andrus et al 1988). LWD can significantly influence channel stability by combinations of all of the above processes:

- Formation of semi-permanent to permanent, stationary log and root steps that dissipate energy, store bed load and stabilise bed profiles (Heede 1972, 1981, Keller & Swanson 1979, Mosley 1981, Marston 1982, Erskine 1986a, Lisle 1986, Thompson 1995, Wohl et al 1997);
- Creation of large scale roughness elements that dissipate energy and decrease flow velocity (Hickin 1984, Gregory 1992, Nanson et al 1995);
- Increase bank resistance and near bank roughness, thus retarding bank erosion (Smith 1976, Keller & Swanson 1979); and

- Formation and spacing of pools (Lisle 1986, Andrus et al 1988, Robison & Beschta 1990, Thompson 1995, Montgomery et al 1995).

LWD also serves many ecological functions (Gregory 1992, Gregory & Davis 1992, O'Connor & Lake 1994). Many native tree and shrub species readily coppice when damaged by floods (Nanson et al 1995) and hence can not only survive significant flood damage but can also stabilise eroded sections (Erskine 1986a). The importance of log steps decreases with increasing catchment area as channel size also increases and individual logs are no longer capable of spanning the whole channel (Keller & Swanson 1979, Heede 1981, Marston 1982, Wohl et al 1997).

While the above literature indicates that riparian vegetation and LWD can interactively stabilise channels and floodplains, the mechanisms actually operating in the channels flanked by riparian forests in the Swift Creek catchment need quantification. The forested reaches (table 3) would not be stable except for the trees and LWD. The total LWD loading, the effects of LWD on bed and bank stability and pool formation, recruitment processes of LWD, riparian vegetation and its influence on channel stability should all be determined for the reaches with significant riparian vegetation (forested reaches in table 3). As most of these reaches are upstream of the mine site, they will not be impacted in the immediate future. Therefore, this project can be started after some of the above projects have been completed.

7 Conclusions and recommendations

7.1 Conclusions

The 13 sub-projects outlined above are designed to determine the hydrologic, sedimentologic and geomorphic baseline characteristics of catchments in the Jabiluka Mineral Lease, as well as the physical impacts of uranium mining on Swift Creek. They complement and extend the previous research undertaken by ***eriss*** and other agencies at Ranger uranium mine and in the Alligator Rivers Region (see Erskine & Saynor (2000) for a review of previous research). Additional site-specific work is also required to monitor and measure the environmental impacts of the mine and to derive appropriate data for the calibration of landscape evolution models and for mine management. These models are not only required for environmental impact assessment but also for a meaningful assessment of the long-term stability of rehabilitated landforms at the conclusion of mining.

7.2 Recommendations

The Extreme Events Project recommended by Erskine and Saynor (2000) for the Ranger mine should be undertaken in addition to the above sub-projects because such information is also required for the design of a stable rehabilitated mine site at Jabiluka. Catastrophic floods also profoundly influence suspended sediment dynamics and bed load transport and storage. Pickup et al (1987) recommended that information on extreme events should be compiled and some of their specific projects have not been completed to date. Erskine and Saynor (2000) also found an additional site for such work which was not inspected by Pickup et al (1987).

The above sub-projects represent a comprehensive program of environmental impact assessment of the Jabiluka uranium mine. Results from these sub-projects should be published as Supervising Scientist Reports as well as peer-reviewed papers in international and national journals so that the consolidated database and information are freely available for public scrutiny.

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