ENVIRONMENTAL IMPACT OF MINING

Erosion and Hydrology

Temporal trends in erosion and hydrology for a post-mining landform at Ranger Mine

DR Moliere, KG Evans & GR Willgoose[1]

Background

An important part of rehabilitation planning for mines is the design of a stable landform for waste rock dumps or spoil piles, at the completion of mining, which minimise erosion and environmental impact offsite. To successfully incorporate landform designs in planning it is useful to predict the surface stability of the final landform using erosion and landform evolution modelling techniques (Evans et al 1998). Previous studies by Willgoose and Riley (1998) and Evans et al (1998) have used the landform evolution model, SIBERIA (Willgoose et al 1989), to simulate the erosional stability of the proposed 'above-grade' rehabilitated landform at the Energy Resources of Australia Ranger Mine (ERARM), Northern Territory, for a period of 1000 y.

Willgoose and Riley (1998) and Evans et al (1998) used input parameter values derived from data collected from areas of the waste rock dump (WRD) at Ranger and these input parameter values were assumed to remain constant throughout the period that was simulated (1000 y). In other words, changes in erosion rate resulting from processes such as soil and ecosystem development and armouring on the landform surface were not simulated.

Studies such as Jorgensen and Gardner (1987), Ritter (1990) and Loch and Orange (1997) confirm and describe the change in erosion rates on reclaimed mine sites with time. Therefore, in this study an attempt has been made to quantitatively assess how erosion and hydrologic characteristics of landforms, and hence SIBERIA parameter values, are affected by temporal change.

Study site

The Ranger Mine lease boundary is located in the wet-dry tropics of the Northern Territory, Australia, and is surrounded by the World Heritage-listed Kakadu National Park (see map on page 4). ERARM is approximately 230 km east of Darwin and 10 km east of Jabiru (see map on page 4). The average annual rainfall for Jabiru is approximately 1483 mm (Bureau of Meteorology 1999) and most of the rainfall in the region occurs during a distinct Wet season from October to April.

Data were collected from the following sites. These sites were considered to be representative of the surface hydrology and erosion characteristics that would exist on the WRD at Ranger mine at various stages after rehabilitation.

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1 An area on the batter slope on the WRD at Ranger mine (WRD_0) (Evans et al 1998) was assumed to represent the proposed final rehabilitated condition immediately after mining is completed.

2 Two areas on the WRD at the abandoned Scinto 6 uranium mine (Moliere 2000) (see map on page 4) — one with concentrated flow conditions (WRD_{50C}) and the other with sheet flow conditions (WRD_{50S}) — were assumed to represent the surface condition at Ranger mine 50 years after rehabilitation.

3 Two natural, undisturbed channelised catchments in sparse, open woodland at Tin Camp Creek (Riley 1994) (see map on page 4), $Nat_{C(1)}$ and $Nat_{C(2)}$, were assumed to represent the Ranger mine surface condition after rehabilitation in the long term under concentrated flow conditions.

4 A natural, undisturbed area of bushland approximately 50 m south of Pit 1, Ranger mine, (Nat_S) (Bell & Willgoose 1997), was assumed to represent the surface condition at Ranger mine after rehabilitation in the long term under sheet flow conditions.

The batter slope on the WRD would initially be constructed during rehabilitation as a planar surface with sheet flow conditions. In time the batter slope could have two evolutionary paths (fig 1): (1) the surface will remain planar under sheet flow conditions, and (2) the surface will become incised under concentrated flow conditions.

If, as time passes after rehabilitation, runoff is directed away from the batter slope and the surface only receives direct rainfall, the site should retain a planar surface with sheet flow conditions. As soil and ecosystem development occurs at Ranger mine in the short term, the WRD_0 surface condition will change towards that similar to the surface condition of WRD_{50S}. In the long term, the surface condition of the landform at Ranger mine will evolve to that similar to the surface condition of Nat_S (fig 1).

However, if overland flow from the upper WRD surface breaches the bund at the top of the batter slope and flows over the surface then channelised flow will occur and a gully may develop. As soil and ecosystem development occurs at Ranger mine in the short term under concentrated flow conditions, the WRD_0 surface condition will change towards that similar to the surface condition of WRD_{50C}. In the long term the surface condition of the landform at Ranger mine will evolve to that similar to the surface condition of Nat_C (fig 1).

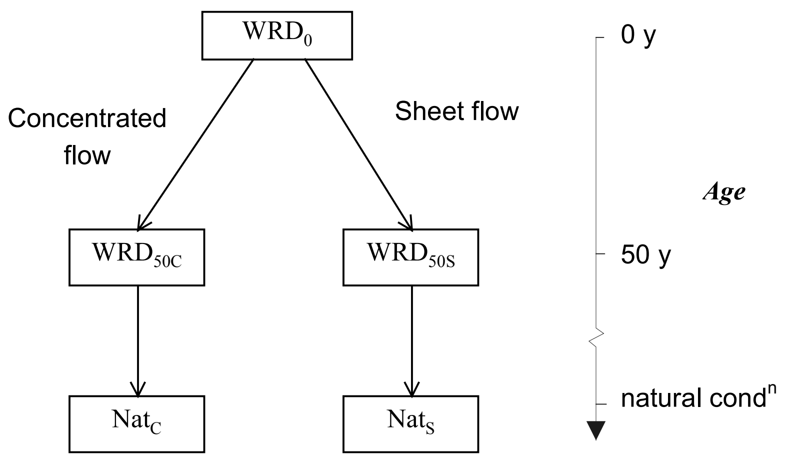

Figure 1 A schematic representation of the evolutionary paths of the batter slope at Ranger mine under concentrated flow and sheet flow conditions

SIBERIA model

The SIBERIA landform evolution model developed by Willgoose et al (1989) is a computer model designed for examining the erosional development of catchments and their channel networks.

Figure 2 shows a flow diagram of the parameter derivation process for input into the SIBERIA model. Parameter values used in SIBERIA can be classified as *primary* and *secondary*. The primary parameters in SIBERIA modelling represent the hydrologic and erosion characteristics of the site where monitoring data are collected. The secondary parameters are dependent on the primary parameter values fitted for a site and represent the long-term average SIBERIA model parameter values for the landform being modelled.

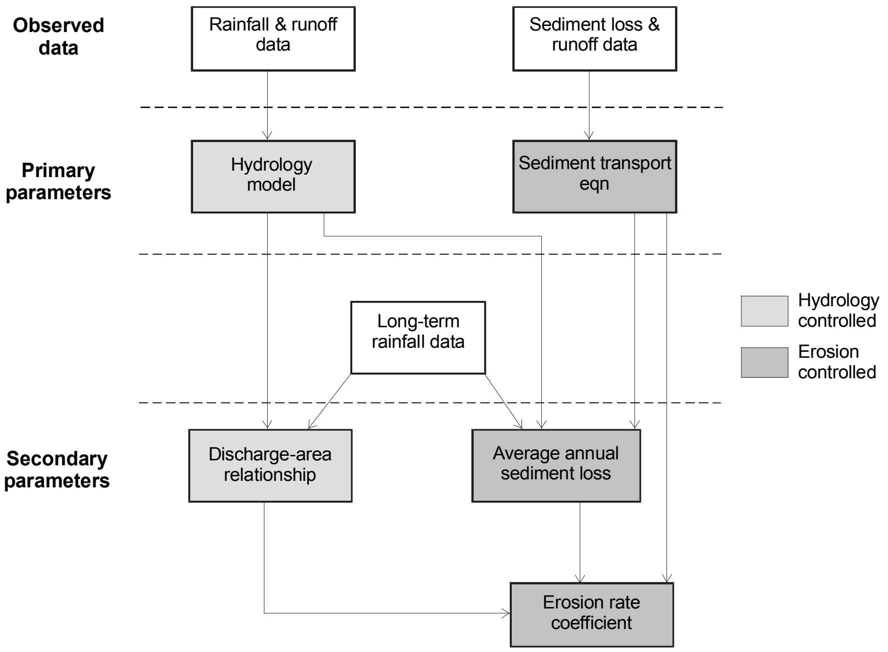

Figure 2 Flow diagram representing the SIBERIA input parameter derivation process. The shaded boxes indicate parameters that are hydrology or erosion controlled.

To obtain the primary parameter values field monitoring data are required to (1) calibrate a hydrology model using rainfall and runoff data from field sites, and (2) fit parameters to a sediment transport equation using sediment loss and runoff data from field sites, as described by Willgoose and Riley (1998), Evans et al (1998) and Moliere (2000).

Using long-term rainfall data for the region, the calibrated hydrology and erosion models for each study site (primary parameters) are used to derive long-term average SIBERIA model parameter values for the landform being modelled (secondary parameters) which, for this study, is the proposed rehabilitated landform at Ranger mine.

Temporal effect on SIBERIA model parameter values

Parameters fitted to the hydrology model and the discharge-area relationship (fig 2) represent the hydrological characteristics of the landform. These hydrology controlled parameter values fitted for each study site condition were all similar (Moliere 2000). This indicates that the model will simulate no significant change in the hydrological characteristics of the landform at Ranger mine with time.

However, it has been demonstrated that the parameter values that represent the erosion characteristics of the landform — those fitted to the sediment transport equation, the average annual sediment loss and the erosion rate coefficient (fig 2) — will change in time (fig 3). The change is rapid and occurs within the first 50 years after mining is completed, after which the parameter values return to near that of the natural landform under both concentrated flow and sheet flow conditions (fig 3). The temporal trend in these parameter values reflect the change in erosion rate with time likely to occur on the landform at Ranger mine due to factors such as compaction, surface armouring and soil and ecosystem development. It is important to incorporate the 'short-term' change in these input parameter values within landform evolution modelling to better predict the stability of the rehabilitated landform at Ranger mine for a 1000 y simulation period.

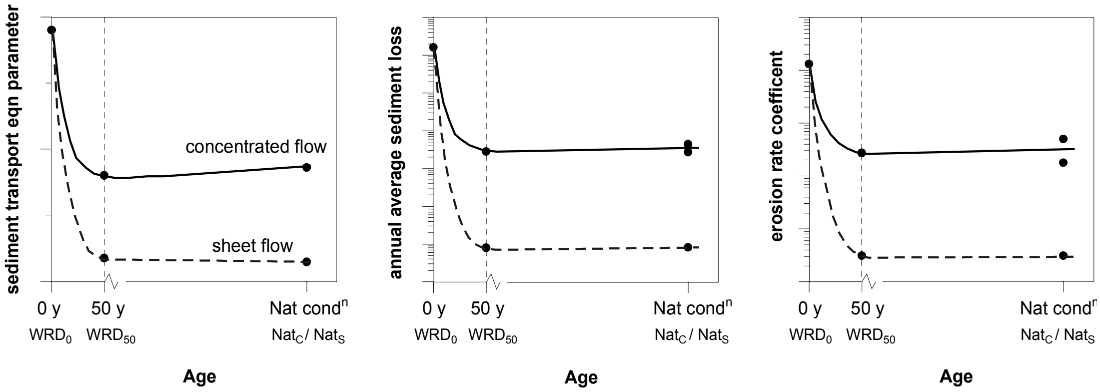

Figure 3 Erosion rate parameter values at various times after rehabilitation at Ranger mine. Approximate lines of best fit for the concentrated flow (bold) and sheet flow (dashed) conditions are also shown.

The landforms predicted at 1000 y using parameter values that change with time are shown in figure 4 and provide a current 'best estimate' of the stability of the proposed landform at Ranger mine in the long term under two different flow conditions.

SIBERIA modelling was also used to predict the valley development on the landform at 1000 y using parameter values fitted for the zero year surface condition (WRD_0). Using parameter values fitted for the WRD_0 condition it was assumed that, similar to previous studies at Ranger mine (Willgoose & Riley 1998, Evans et al 1998), there was no soil and ecosystem development on the surface of the landform and therefore the parameter values would remain constant for the simulation period (1000 y). This is a 'worst-case' scenario for the rehabilitated landform at Ranger mine (fig 4).

The difference between the overall valley development on the two best estimate landforms (fig 4) reflects the difference in erosion rate parameter values at 50 y after rehabilitation (fig 3). Using parameter values fitted for the zero year surface condition to model the rehabilitated landform, and assuming no soil and ecosystem development for the simulation period, will over-predict the long-term stability of the landform at Ranger mine, particularly under sheet flow conditions. Therefore, the worst-case scenario for the landform at 1000 y is a conservative prediction of landform stability at Ranger mine.

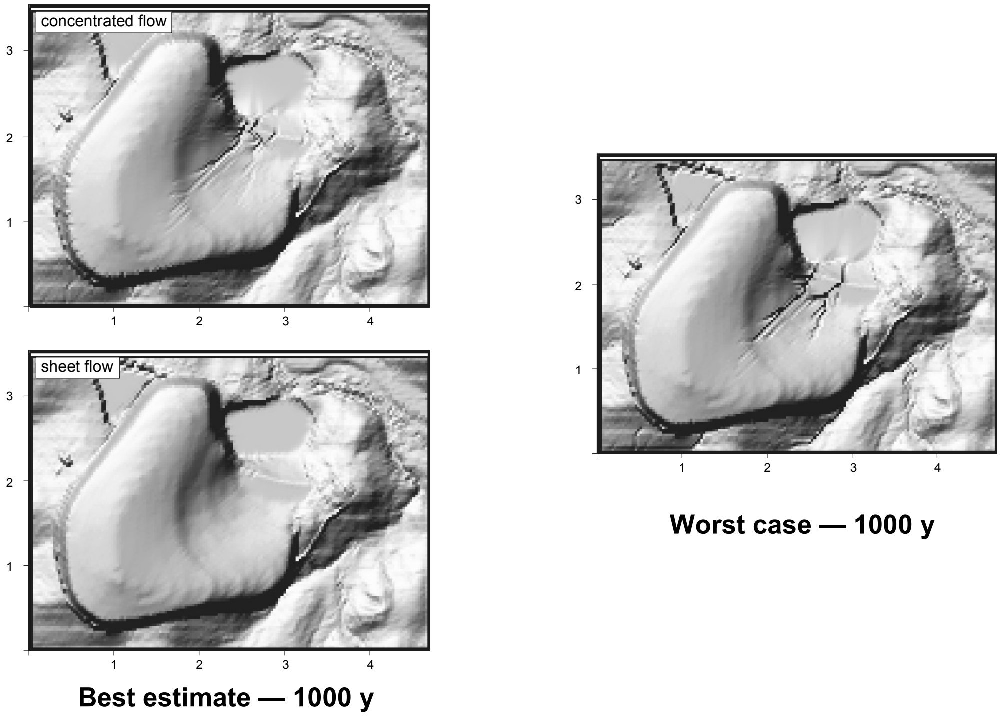

Figure 4 3-D representation of the valley development at Ranger mine at 1000 y using parameter values that (1) change with time under both concentrated and sheet flow conditions (best estimate); and (2) were fitted for the zero year surface condition (worst-case). Dimensions are in kilometres.

Conclusions

The erosion rate on the proposed landform at Ranger mine is likely to change with time over the long term and this study has been able to quantify these changes in terms of SIBERIA parameter values. The incorporation of these temporal changes in parameter values into the SIBERIA model has provided a best estimate of the stability of the landform at Ranger mine over a 1000 y simulation period. This is a significant advance in landform evolution modelling of a post-mining landform.

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Suspended sediment loads in the receiving catchment of the Jabiluka uranium mine site, Northern Territory[1]

DR Moliere, KG Evans, MJ Saynor & WD Erskine[2]

Introduction

The Jabiluka uranium mine is located in the catchment of Ngarradj[3] in the wet-dry tropics of the Northern Territory, Australia (fig 1). Ngarradj is a major downstream right-bank tributary of Magela Creek, which flows directly into the Magela Creek floodplain. The Magela Creek and floodplain are listed as Wetlands of International Importance under the Ramsar Convention and recognised under the World Heritage Convention.

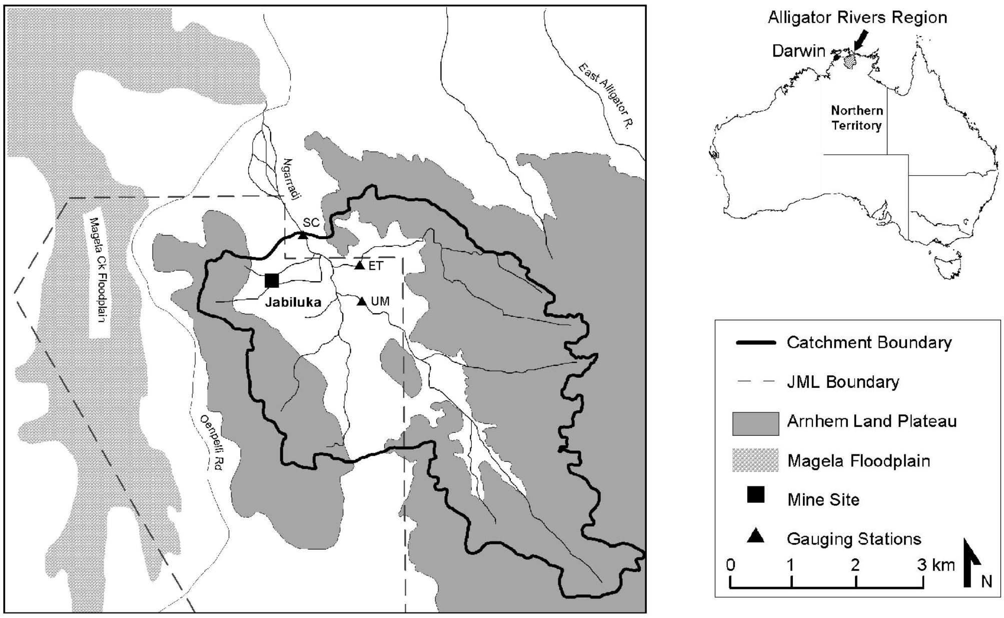

Figure 1 The Ngarradj catchment and tributaries showing the Jabiluka Mineral Lease and the gauging station sites (prepared with assistance from G Boggs, NTU)

The Ngarradj catchment will be the first to be affected should any impact occur as a result of mining operations at Jabiluka. Responsible catchment management and mining impact control requires an understanding of contemporaneous catchment baseline conditions of sediment movement and hydrology. Therefore, a stream gauging network was established in 1998 to collect data on discharge and sediment transport in the Ngarradj catchment (fig 1).

1 This paper appears in *Proceedings of the Hydro 2000 Conference on Interactive Hydrology*. Institution of Engineers, Perth, November 2000, 564–569.

2 Environmental Management & Forest Practices Directorate, State Forests of NSW, Locked Bag 23, Pennant Hills, NSW 2120 (now Office of the Supervising Scientist).

3 Ngarradj: Aboriginal name for the stream system referred to as 'Swift Creek' in earlier studies. Ngarradj means sulphur crested cockatoo. The full term is Ngarradj Warde Djobkeng. Ngarradj is one of several dreaming (Djang) sites on or adjacent the Jabiluka mine lease (A Ralph, Gundjehmi Aboriginal Corporation 2000).

Stream gauging stations were installed upstream (Upper Main — UM; East Tributary — ET) and downstream (Swift Creek — SC) (fig 1) of the mine in order to assess before and after impact. A specific aim of this work is to calibrate an erosion model that can be used for long-term integrated catchment management of the Jabiluka Mineral Lease with respect to suspended sediment transport.

This paper presents the calibration process of a sediment transport equation for the SC gauging site that can be used to derive a reliable and statistically significant prediction of suspended sediment loss.

Ngarradj data

Stream discharge was derived from observed stage height and velocity-area gauging data collected during the 1998/1999 and 1999/2000 Wet seasons. A stage activated pump sampler was installed at each station to obtain detailed time series variations in sediment concentrations required for accurate load determinations (Rieger & Olive 1988).

During the 1998/99 Wet season the suspended sediment data set collected at the SC gauging station was not sufficient to determine a total annual suspended sediment loss. Gaps in the suspended sediment data set were particularly evident during the periods of intense rainfall-runoff events because the capacity (ie number of bottles) of the pump sampler was exceeded (fig 2).

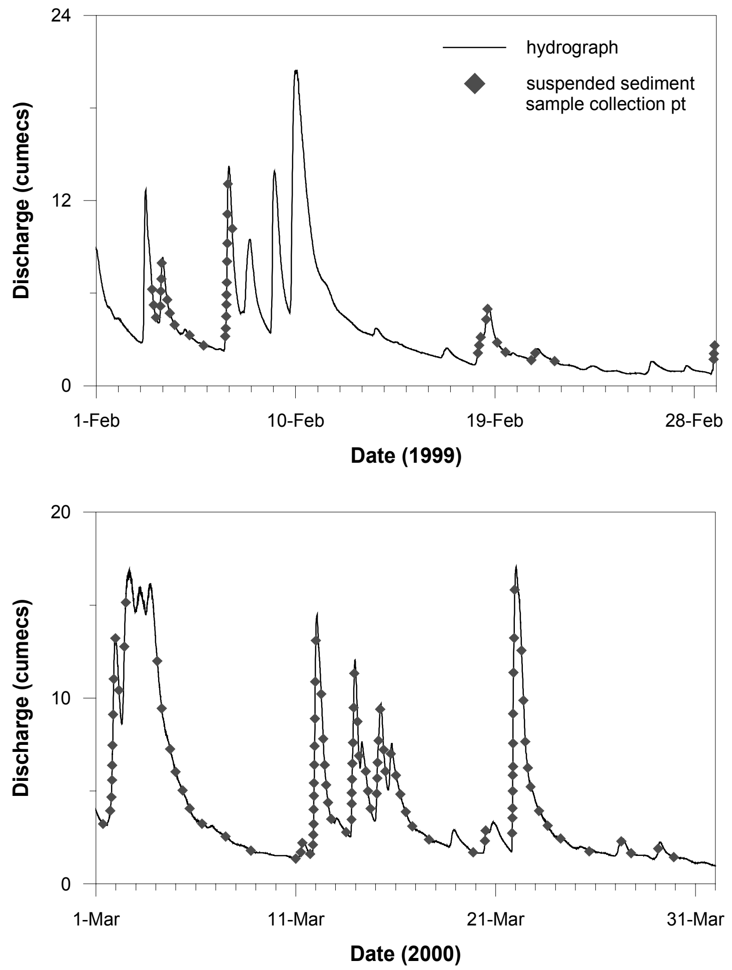

Figure 2 Hydrograph and suspended sediment sample collection points (♦) during intense rainfall-runoff periods in February 1999 (Top) and March 2000 (Bottom) at SC (Swift Creek)

In order to collect continuous suspended sediment data throughout the Wet season hydrograph at the SC gauging station, a second stage activated pump sampler was installed before the 1999/00 Wet season.

As a result, the suspended sediment data set collected during the 1999/00 Wet season at the SC gauging station was sufficient to determine a total annual suspended sediment loss. Figure 2 illustrates the hydrograph showing collection points of the sediment samples during an intense rainfall-runoff period in March 2000, indicating significant improvement in the suspended sediment data set for 1999/00 compared to that collected during 1998/99. This type of sampling distribution was achieved throughout the 1999/00 Wet season. Integration of the sedigraph gave the total observed suspended sediment loss for the 1999/00 Wet season at the SC station as 1179 t.

Sediment transport equation parameterisation

Observed sediment concentration-discharge data from SC (fig 3) were used to fit the following relationship:

$$c = K_2\, Q^{m_2} \qquad (1)$$

where c is suspended sediment concentration (g/L), Q instantaneous discharge (L/s) and m_2 and K_2 are fitted parameters.

The fitted c-Q relationship for the data collected during both 1998/99 and 1999/00 wet seasons at SC is:

$$c = 0.0056\, Q^{0.208} \qquad (r^2 = 0.03) \qquad (2)$$

which is not significant as indicated by the very low correlation coefficient (eqn 2).

Using the runoff data collected at SC during 1999/00 the fitted c-Q relationship (eqn 2) predicts a total suspended sediment loss for the Wet season at the gauging station of 1077 t, which is 91% of the observed suspended sediment load (1179 t). However, when equation 2 is corrected for statistical bias (Ferguson 1986), the predicted total suspended sediment load is 1605 t, which is not similar to the observed suspended sediment load (1179 t).

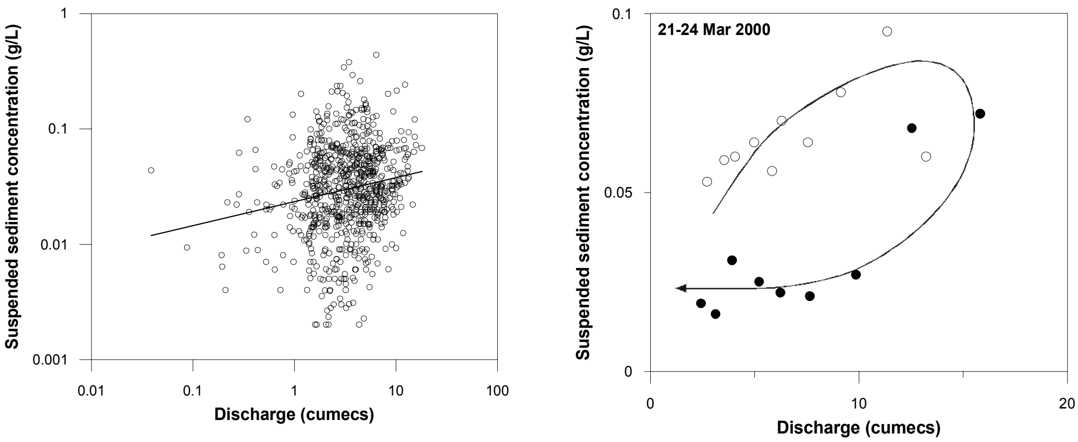

Figure 3 Suspended sediment concentration against discharge at the SC gauging station using (1) two years of monitoring data (the line of best fit (eqn 2) is also shown) (Left); and (2) monitored data from a single runoff event (21–24 March, 2000) where data were collected during the event on both the rising limb of the hydrograph (indicated by ○) and the falling limb of the hydrograph (●) (Right).

The large scatter associated with the data (fig 3) can be partly explained by the hysteresis between *c* and *Q* that occurs during individual storm events monitored on a catchment scale (Walling 1974, 1977). Hysteresis was observed in the SC data (fig 3) where the ratio *c/Q* at any time on the rising limb of the hydrograph is greater than that for the same discharge on the falling limb, introducing a temporal effect in the *c-Q* relationship (eqn 2). The 'clockwise loop' fitted for the individual storm event data (fig 3) has been attributed to sediment depletion before the runoff has peaked (Williams 1989).

Parameter values were fitted to an 'event-based' sediment transport model of the form (Evans et al 1998):

$$T = K_1 \int Q^{m_1} dt \qquad (3)$$

where T = total sediment loss (g), derived by integration of the sedigraph, and $\int Q^{m_1} dt$ = cumulative runoff over the duration of an event (Q = discharge (L/s)). Further research is required to confirm whether this removes temporal effects. Evans et al (1998) used log-log regression to fit equation 3. However, in this study a weighted regression was used where parameters K_1 and m_1 were fitted by trial and error to get a best fit slope of 1 between predicted and observed sediment loss with minimum variance (σ^2).

The monitored runoff and suspended sediment data at SC for both 1998/99 and 1999/00 Wet seasons was sub-divided into 14 discrete events. An event was considered to be a runoff period that started and ended at approximate baseflow conditions and incorporated complete rising and falling stages of the hydrograph. For example, the runoff period between 11–17 March 2000 and the runoff period between 21–24 March 2000 (fig 2) were considered to be two separate runoff events. The total runoff and total observed suspended sediment loss at the SC gauging station for each of the 14 events are given in table 1.

Table 1 Monitored event data at the SC gauging station during 1998/99 and 1999/00

Date	Total runoff (ML)	Suspended sediment loss (t)	Date	Total runoff (ML)	Suspended sediment loss (t)
9 Dec 1998	22.67	0.35	15 Jan 2000	1521.07	34.22
12 Jan 1999	273.70	8.76	23 Jan 2000	1499.18	49.51
25 Jan 1999	401.40	19.40	9 Feb 2000	5051.49	181.69
22 Mar 1999	299.75	10.76	26 Feb 2000	6079.75	278.95
20 Dec 1999	522.68	16.39	11 Mar 2000	2811.65	91.21
26 Dec 1999	2270.60	86.73	21 Mar 2000	1574.00	65.11
6 Jan 2000	1217.10	20.50	24 April 2000	768.75	17.73

An arbitrary value of m_1 was selected and used to determine a value for $\int Q^{m_1} dt$ for each event, which was used in equation 3 for regression analysis. The values of K_1 and m_1 were changed by trial and error until the slope of the best fit line of the linear regression between predicted suspended sediment loss (eqn 3) and observed suspended sediment loss (table 1) was equal to 1 and σ^2 was at a minimum. The values of m_1 and K_1 for this condition were selected as the fitted parameters.

This resulted in the following sediment transport equation for the SC gauging station:

$$T = 0.00136 \int Q^{1.38} dt \; (r^2 = 0.98; \text{no. of obs} = 14; p < 0.001) \qquad (4)$$

Figure 4 shows that the predicted suspended sediment losses (eqn 4) are similar to the observed sediment losses for the 14 runoff events at the SC gauging station. Equation 4 is a statistically significant and reliable sediment loss-discharge relationship for this site. The total predicted suspended sediment loss at the SC gauging station using the observed hydrograph for the 1999/00 wet season in equation 4 is 1133 t, which is 96% of the observed suspended sediment loss of 1179 t.

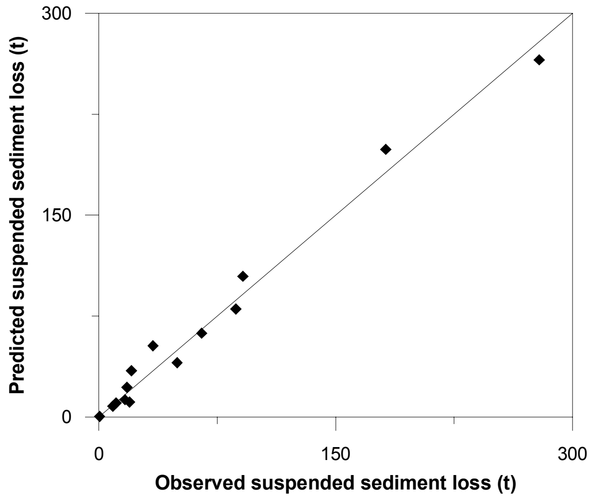

Figure 4 Relationship between observed and predicted suspended sediment loss (eqn 4) at the SC gauging station

Conclusion

In this study, a more reliable and statistically significant prediction of suspended sediment loss at the SC station is obtained using an event based total sediment transport equation instead of a *c-Q* relationship. The total sediment transport equation predicts waves of sediment which should remove the temporal hysteretic effect within individual runoff events.

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Integration of GIS and modelling techniques for impact assessment at Jabiluka Mine, Northern Territory[1]

GS Boggs[2,3], KG Evans, CC Devonport[2] & MJ Saynor

Introduction

This section describes the development and application of a geographic information system (GIS) centred approach to risk assessment that is being used to measure the long-term geomorphological impacts of the Environmental Resources of Australia (ERA) Jabiluka Mine. GIS provides a means by which the data collected during the assessment of possible mining impacts can be stored and manipulated. geographic information systems have been linked with a large number of erosion and hydrology models (de Roo 1998) and used in a limited number of geomorphological impact assessment studies (eg Patrono et al 1995). However, this study differs from many previous studies by adopting a GIS centred approach to the management and manipulation of data generated by a geomorphological impact assessment. The design of the GIS is based on three major functions; (1) data storage, management and retrieval, (2) interaction with environmental modelling techniques, and (3) basin analysis including the geomorphometric analysis of landform evolution (fig 1). Benefits of this approach include the simplification of data maintenance, revision, and update, as well as increasing the accessibility and useability of the data.

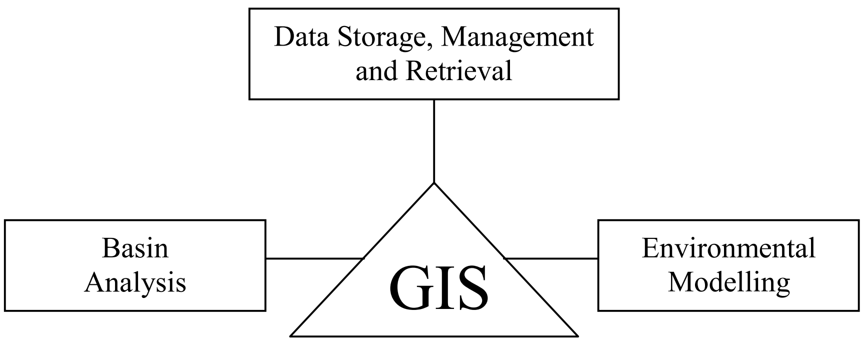

Figure 1 The design of a GIS as a central point for risk assessment

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1 More detailed discussion of this research is provided in Boggs GS, Devonport CC, Evans KG, Saynor MJ & Moliere DR 2001. *Development of a GIS based approach to mining risk assessment*. Supervising Scientist Report 159, Supervising Scientist, Darwin.

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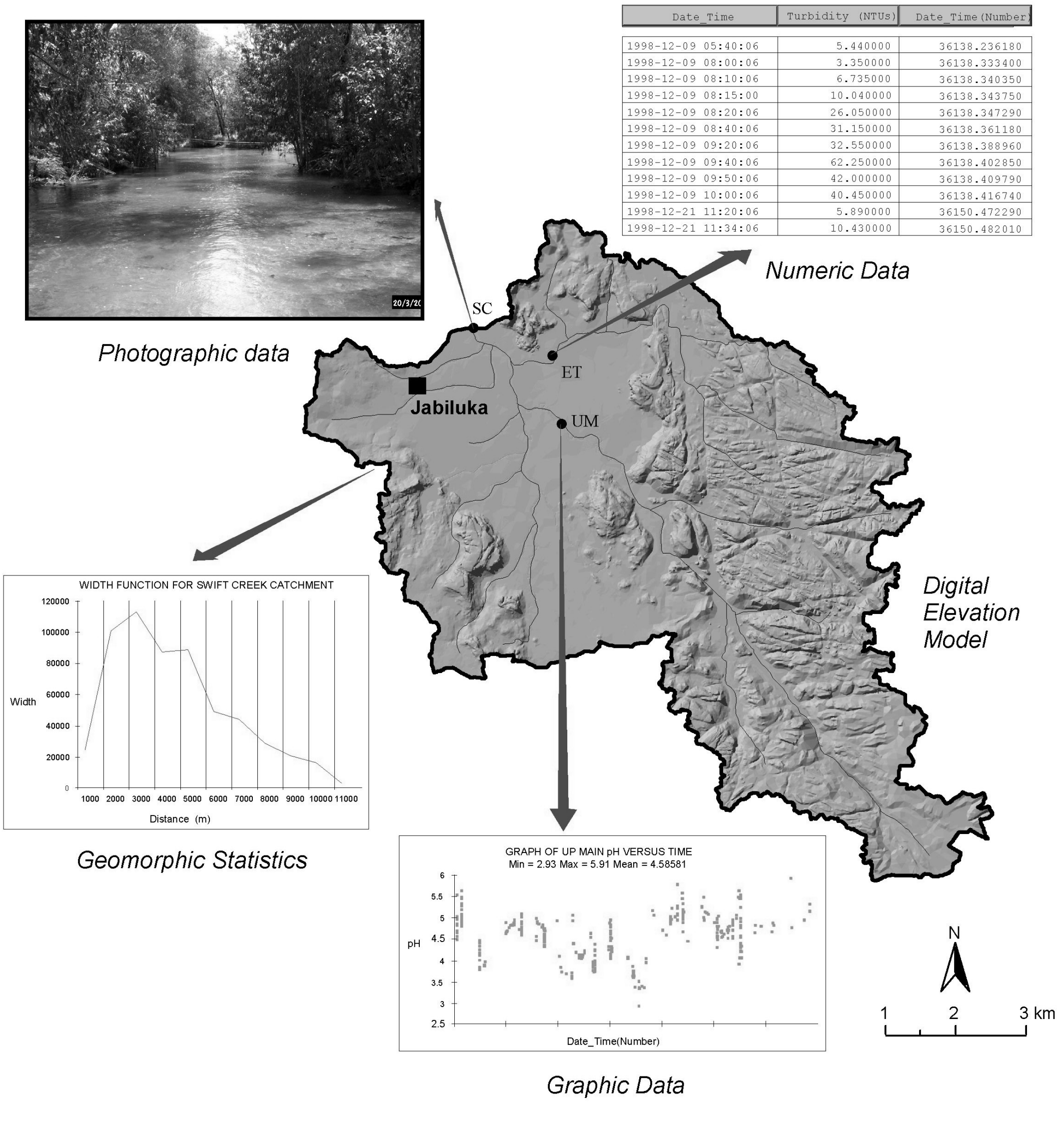
Data storage, management and retrieval

Gauging station data

In November 1998 three stream gauging stations were established within the Ngarradj catchment (fig 2). Data are collected from these stations at frequent intervals, providing a high temporal resolution data source. These data are being used to: (i) monitor for potential impacts of the ERA Jabiluka Mine (Erskine et al 2001) and (ii) to calibrate the SIBERIA landform evolution model (Boggs et al 2000). The approach adopted to store, manage and retrieve these data involved the customisation of the ArcView GIS package to connect the GIS with the Microsoft Access relational database and Microsoft Excel spreadsheet software packages (Boggs et al 1999). The system has been designed to enable data collected during field visits or through laboratory analyses to be entered into an access database linked to the GIS. This allows data to be retrieved through customised dialog boxes embedded within the GIS interface.



Date_Time	Turbidity (NTUs)	Date_Time(Number)
1998-12-09 05:40:06	5.440000	36138.236180
1998-12-09 08:00:06	3.350000	36138.333400
1998-12-09 08:10:06	6.735000	36138.340350
1998-12-09 08:15:00	10.040000	36138.343750
1998-12-09 08:20:06	26.050000	36138.347290
1998-12-09 08:40:06	31.150000	36138.361180
1998-12-09 09:20:06	32.550000	36138.388960
1998-12-09 09:40:06	62.250000	36138.402850
1998-12-09 09:50:06	42.000000	36138.409790
1998-12-09 10:00:06	40.450000	36138.416740
1998-12-21 11:20:06	5.890000	36150.472290
1998-12-21 11:34:06	10.430000	36150.482010

Figure 2 A hillshaded version of the Ngarradj digital elevation model, showing types of data that can be rapidly accessed through the customised GIS interface (SC, ET & UM are stream gauging stations)

The link between the GIS and database allows the user to select a site on the computer screen and interact with the associated databases, importing and graphing data 'on the fly' for the selected site (fig 2). This allows rapid assessment of temporal and spatial trends in the data. Much of the analysis of these data, however, involves complex statistical operations not offered within the standard GIS. An option within the data retrieval dialog box exports data directly from the database to a spreadsheet package, allowing further statistical analysis and more sophisticated graphing operations.

Raster data

Raster data obtained for the Ngarradj project comprise a Digital Elevation Model (DEM), constructed from 1:30 000 pre-mining (1991) aerial photography (fig 2) and remotely sensed imagery (including aerial photography, Landsat TM and MSS imagery). Raster data sets generally utilise large amounts of storage space and thus require large and well-organised data bases. A GIS offers a highly suitable approach for efficient storage, retrieval and analysis of large raster data sets (Schultz 1993). DEMs are currently used in many geomorphologic studies as they allow the extraction of terrain and drainage features to be fully automated (Moore et al 1991). Remotely sensed imagery is considered to be a rapid and flexible method for obtaining updated data, particularly as images are easily stored and interpreted in a GIS. Raster data, therefore, are useful in the examination and explanation of the gauging station data and provide direct inputs into the hydrology and landform evolution models.

Vector data

The vector database established consists primarily of the Topo-250 k digital data product produced by the Australian Surveying and Land Information Group (AUSLIG), with some of the data available at 100 k scale. Additional data layers are related to individual projects and have been obtained in the field or from aerial photography and other imagery. As much of the base vector data are too coarse for investigations at the Jabiluka project scale, the primary vector data source is derived from DEM/remote sensing products and data collected with the use of a differential GPS (Global Positioning System). Differential GPS provides a cost effective, accurate source of raw geographical information valuable in the mapping, field data collection and GIS database construction phases of the geomorphological impact assessment process (Cornelius et al 1994). Differential GPS, along with aerial photography interpretation, has been successfully used in initial channel reach characterisation and geomorphic mapping of the Ngarradj (Swift Creek) catchment. In a project of this scale, the use of a differential GPS to geo-referenced field sites is considered crucial to the GIS-centred data management approach as all data are linked to specific spatial locations, facilitating the incorporation of all field project data into the information management system.

Geomorphological modelling with GIS

Currently three environmental models are employed in the assessment of mine site landform stability and off-site geomorphological and environmental impacts: 1) a basic sediment transport model, 2) the Distributed Field Williams (DISTFW) hydrology model (Field & Williams 1987), and 3) the SIBERIA landform evolution model (Willgoose et al 1991).

The sediment transport model is an equation that does not have a spatial component and is therefore not appropriate for implementation within a GIS. However, the DISTFW hydrology model is a distributed model that operates on a sub-catchment basis, whilst the SIBERIA landform evolution model is based on a DEM. The integration of these two models with the GIS has used the loose coupling and tight coupling methods respectively. The ArcView GIS package has been customised to facilitate these levels of integration between the models and the GIS.

DistFW hydrology model

Hydrologic analysis has been integrated with computers to such an extent that computers often provide the primary source of information for decision-making by many hydrologic engineers (deVantier & Feldman 1993). Linking the DISTFW hydrology model with a GIS using a loose coupling approach primarily involves the development of a GIS toolbox that will allow the automatic generation of DISTFW input requirements.

The DISTFW hydrology model requires the input of a significant amount of topographic information. Catchments are represented within the model as a number of sub-catchments for which information must be derived describing their horizontal shape, vertical relief, conveyance and the flow relationships between individual sub-catchments. A significant challenge in this research project has been to develop a set of customised tools that automatically generates this information primarily from a DEM. Six software tools have now been developed that extend the functionality of the ArcView GIS to satisfy the topographic input requirements of the DISTFW hydrology model (Boggs et al 2000).

SIBERIA landform evolution model

SIBERIA models the evolution of a catchment through operations on a DEM for the determination of drainage areas and geomorphology. GIS offer a wide range of raster data processing capabilities and a clear means for organising and visualising data from a number of different formats (Rieger 1998). Linking the SIBERIA landform evolution model with GIS therefore provides benefits not available in one or other of these environments. In particular, integrating the SIBERIA model with a GIS enhances the 'user-friendliness' and functionality of the model, which would not otherwise lend itself to interactive use. The approach adopted to link SIBERIA with a GIS maintains the two technologies as separate entities that share a user friendly front end and database.

The suite of tools developed to link SIBERIA with the ArcView GIS package have been assembled into an ArcView extension named 'ArcEvolve'. Extensions are add-on programs that provide additional functionality to ArcView through the addition of menu items, buttons and/or tools. The functionality associated with the added menus/button/tools is derived from scripts written in the ArcView object-oriented programming language 'Avenue'.

ArcEvolve allows the user to interact with SIBERIA through the addition of a menu ('SIBERIA') to the ArcView 'View' document graphical user interface (GUI). The menu contains a number of items that:

- allow SIBERIA native format files to be imported and exported. The digital elevation model data and parameter values contained in a SIBERIA restart file (rst2) can be imported into an ArcView grid and associated database respectively. SIBERIA boundary files, which contain information for an irregularly shaped region can be imported or created from an ArcView grid.
- provide access to dialog boxes for the creation and management of a SIBERIA parameter database. A new database can be created and parameters imported, with each record being linked to a grid. A series of nine dialog boxes, which can be accessed from the View GUI, provide a user-friendly frontend for updating the parameter database for a selected grid.

- Run the SIBERIA model, with output imported into ArcView following the completion of the model run

Basin analysis

Geomorphometry, defined as the 'quantitative treatment of the morphology of landforms', (Morisawa 1988) has expanded significantly since its inception over 50 years ago (Morisawa 1988). The advent of the DEM has allowed geomorphometry to not be limited to the time-consuming measurement of landform properties from contour lines on topographic maps. The DEM has allowed the development of algorithm's that rapidly derive such measures and has also allowed the definition of a number of new morphometric measures (Nogami 1995). The width function, hypsometric curve, cumulative area distribution and area-slope relationship are four geomorphometric measures that can be rapidly derived from a DEM and have been shown to be important measures of catchment geomorphology and hydrology. These descriptors have also been successfully used to quantify and compare SIBERIA derived landscapes with natural landscapes (Hancock et al 2002). This study represents the first attempt to apply these measures to assessing the impact of mining on catchment evolution.

A number of tools for the geomorphometric analysis of digital elevation data (the primary input and output of SIBERIA) have been developed or included as part of the ArcView extension ArcEvolve. The tools, contained in a second menu, 'Geomorph', allow geomorphic descriptors including the width function, hypsometric curve, cumulative area diagram and area-slope relationship to be calculated. The tools also allow the direct comparison of two SIBERIA output DEMs by the calculation of the denudation rate and volumetric difference between two surfaces.

Conclusions

A GIS centred approach to risk assessment has been developed that will be used for a geomorphological investigation into the impact of the ERA Jabiluka Mine on the Ngarradj catchment. A GIS based approach to data management simplifies data maintenance, revision, and update, as well as facilitating data availability and access for users. Furthermore, linking the GIS to the DIST-FW hydrology model and SIBERIA landform evolution model provides a more user-friendly approach to landform evolution modelling whilst contributing significant pre-processing and analysis capabilities to the modelling process.

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An erosion assessment of the former Nabarlek uranium mine, Northern Territory

MK Grabham[1,2], GR Hancock[1] & KG Evans

An appraisal of the rehabilitated landsurface of the former Nabarlek uranium mine was conducted to assess the site from a soil erosion perspective as part of an independent assessment commissioned to evaluate the overall success of rehabilitation of the site. Determination of the gross erosion occurring on the site, sediment discharge to Cooper Creek and the resultant concentration of sediment in Cooper Creek were the primary objectives of the study. These objectives were achieved through the application of several models which used parameter values collected from the Nabarlek site during the Dry season of 2000.

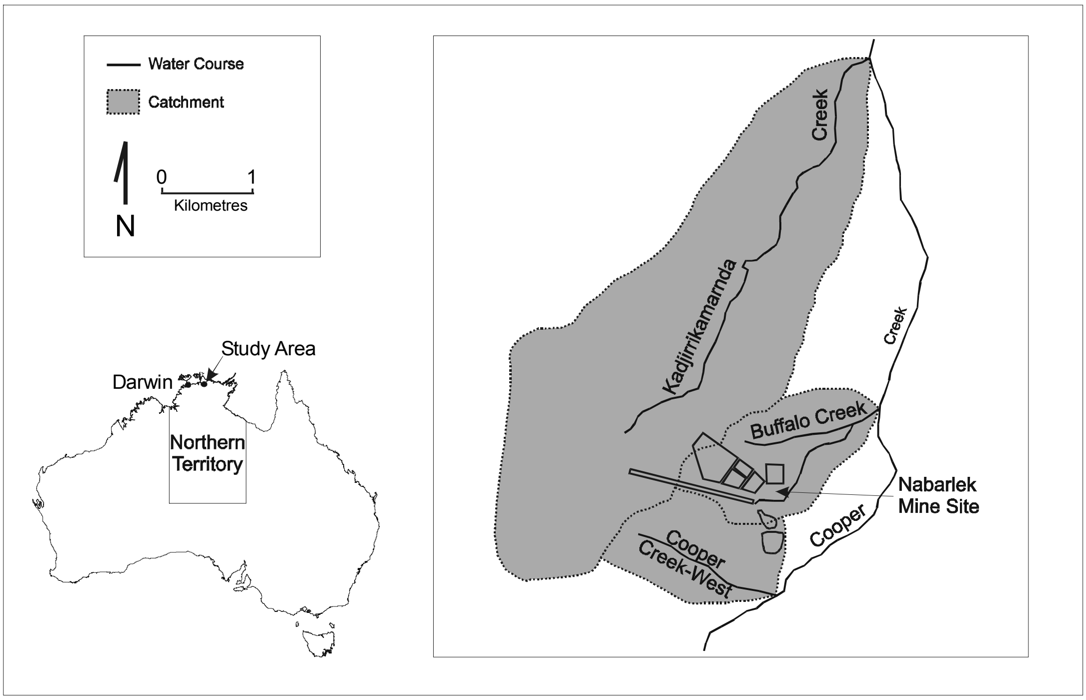

Figure 1 Location and catchments of the former Nabarlek uranium mine

The Nabarlek mine site is located 270 km east of Darwin near the western edge of Arnhem Land. History of the site has been described by Waggitt (2000). The 173 hectare site lies within the catchments of the Cooper (west), Buffalo and Kadjirrikamarnda Creeks (fig 1). These three catchments drain into Cooper Creek which in turn discharges into the mouth of the East Alligator River. Cooper Creek drains 25 240 hectares above its confluence with Kadjirrikamarnda Creek. The catchment is composed of undulating plains of red and yellow soils and siliceous sands with the upper sections of the catchment draining the escarpment areas of the Arnhem Land plateau (Galloway 1976, Needham 1982, Riley 1995). The vegetation is described as open dry-sclerophyll forests (Story et al 1976).

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Methods

The Revised Universal Soil Loss Equation (RUSLE) (Renard et al 1994) was used to determine the gross erosion occurring on the Nabarlek site. This model has been applied to mining applications in the Northern Territory (Riley 1994, Evans & Riley 1994, Riley 1995, Evans & Loch 1996, Evans 1997, Evans 2000) and its predecessor — the Universal Soil Loss Equation (USLE) — was used to design the final landform at Nabarlek (Riley 1995). This not only provides opportunity for monitoring the predictive success of the RUSLE, but also indicates the applicability of the model to the tropical environment of northern Australia (Riley 1995).

The RUSLE is given as:

$$A = RKLSCP \qquad (1)$$

where A is the annual average soil loss (Mg ha^{-1} year^{-1}), R is the rainfall factor expressed as an erosion index (EI) (MJ mm (ha hour year)$^{-1}$), K is the soil erodibility factor (Mg ha hour (ha MJ mm)$^{-1}$), LS is the slope-length and slope-steepness factor (dimensionless), C is the cover and management factor (dimensionless), and P is the conservation practice factor (dimensionless) (Renard et al 1994, Rosewell & Loch 1996).

To successfully apply the RUSLE to a variable landscape, such as the Nabarlek site, it is necessary to divide the area up into homogeneous sub-areas (Wischmeier 1977). Twelve sub-areas or 'erosion units' were determined using the primary components of the RUSLE as the discriminating factors. The gross erosion occurring on each of these twelve units was then calculated and the results added to provide a gross sediment loss estimation for the site.

A percentage of the annual gross erosion from within a catchment arrives at the catchment outlet each year (Robinson 1977, Walling 1983). The remaining sediment is held in depositional areas of a catchment as part of the progressive cycle of detachment, deposition and re-entrainment of the eroded material. To quantify the proportion of the gross erosion released from a catchment requires the application of a Sediment Delivery Ratio (SDR).

The derivation of effective SDRs has proved illusive (Walling 1983, Naden & Cooper 1999) resulting in a lack of models with universal application (Walling 1983). Consequently an SDR developed in the Alligator Rivers Region (ARR) was applied. Evans (2000) derived the SDR for Gulungul Creek in the ARR using the catchment area data of Robinson (1977). The proximity of this location to the Nabarlek site and its ease of application makes this SDR ideal. The ratio is given as:

$$SDR = (8.33 - 0.51 \ln A)^2 \qquad (2)$$

where A is the catchment area (ha).

To determine sediment concentration it is necessary to calculate discharge. Discharge can be determined using a hydrological model, of which there is a vast array (Ward & Robinson 1990). A simple model found to provide reliable mean annual discharge results for Gulungul Creek (Evans 2000) and other locations in the ARR (Duggan 1994) was implemented at the Nabarlek site. This model is expressed as:

$$Q = C_r RA \qquad (3)$$

where Q is the mean annual discharge (m^3 year^{-1}), C_r is a runoff coefficient, R is the average annual rainfall (m year^{-1}) and A is the catchment area (m^2). The C_r factor is dependent on the topography, geology and size of a catchment (Ward & Robinson 1990) and was determined to be 0.43 in undisturbed areas of the catchment and 0.1 for the disturbed areas of the Nabarlek catchment.

Natural sediment loss can be calculated by using a denudation rate. As denudation rates are location specific it is necessary to use a value which has been derived from local topography. There are several values which have been determined for the ARR. These values range from 0.01 mm yr^{-1} (Airey 1983) to 0.04 mm yr^{-1} (Cull et al 1992). Erskine and Saynor (2000) determined the denudation rate for Swift Creek (Ngarradj), an area of similar topography to Cooper Creek, to be 0.016 mm yr^{-1}. This value has been used to determine the sediment yield from natural areas of the Cooper Creek catchment.

Sediment loss from the Nabarlek site was assessed under two scenarios. The first scenario assessed the site under the conditions that were present at the time of sampling. This scenario is referred to as the vegetated scenario. The second scenario assumes no vegetation cover is present thereby simulating the site under burnt conditions. This was carried out as the Nabarlek area has a fire recurrence interval of between one in every two years and one in every three years. As total removal of all vegetation cover is unlikely, this scenario provides a 'worst case' situation.

Results

RUSLE results predict that, under vegetated conditions, there is an average of 31, 335 and 133 tonnes per year of sediment removed from the Nabarlek site into the Cooper-west, Buffalo and Kadjirrikamarnda Creek catchments respectively. Under non-vegetated conditions there is an average of 227, 1238 and 190 tonnes per year of sediment removed respectively. Using a natural denudation rate of 0.016 mm yr^{-1} and catchment discharge values, the background stream sediment concentration for the streams draining Nabarlek is 33 mg L^{-1}. Background, vegetated and non-vegetated sediment concentration for the respective catchments are shown in figure 2.

The background stream sediment concentration in Cooper Creek at the mouth of the three catchments draining Nabarlek is 33 mg L^{-1} given a denudation rate of 0.016 mm yr^{-1} and the annual discharge. The change in sediment concentration as a result of sediment influx from the rehabilitated site is simply a dilution of the above mentioned catchment sediment concentrations. The estimated stream sediment concentration at each of these confluences is illustrated in figure 2.

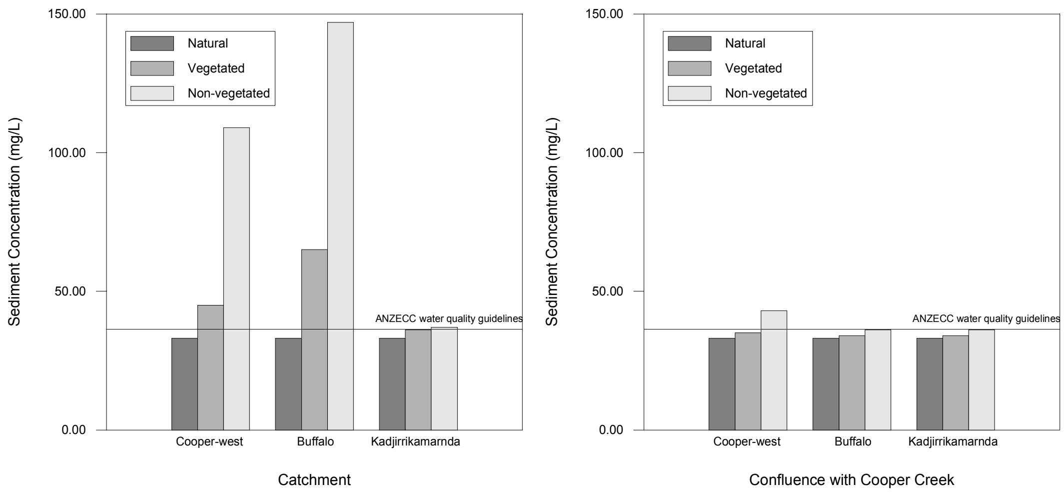

Figure 2 Sediment concentration in catchments draining Nabarlek mine site (left), stream sediment concentration in Cooper Creek at catchment confluences (right).

Discussion

Gross erosion on the Nabarlek site is higher than that occurring on natural areas of the catchment. However, the results show the site to be eroding at a rate close to that predicted by Riley (1995). This suggests that the rehabilitated landscape will maintain its integrity for the recommended design life of 1000 years (DASETT 1987). Furthermore, the average sediment concentration in Cooper Creek is generally within 10% of natural sediment concentration as per the ANZECC water quality guidelines. However, stream sediment concentrations in the catchments draining the Nabarlek site — Cooper-west, Buffalo and Kadjirrikamarnda Creeks — may exceed water quality guidelines. The high sediment concentrations predicted for these catchments were based on non-vegetated conditions and therefore represent a worst case scenario.

The sediment concentration predictions in this study failed to take into consideration the presence of sediment containment ponds which are present on some of the streams draining Nabarlek. While the initial sediment concentration will be lower as a result of sediment containment, the ponds may eventually be breached leading to the subsequent discharge of the sediment to Cooper Creek. In addition to these structures, the impact of feral animals on the site has not been taken into consideration. There is extensive evidence suggesting the presence of both feral pigs and horses on the Nabarlek site. The disturbance of the soil surface by these animals may contribute to the sediment yield from the site.

To evaluate the accuracy of the results in this report, monitoring of the site is necessary. Plot studies and the installation of devices such as erosion pins would provide adequate results to compare with the theoretical predictions in this report. The monitoring of gully development using surveying techniques would provide information on development rates and provide an effective monitoring program for the Nabarlek site.

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Sediment loss from a waste rock dump, Ranger mine, northern Australia[1]

MJ Saynor & KG Evans

Introduction

At the conclusion of mining at the Ranger Mine, it is planned to isolate tailings from the environment for at least 1000 years (East et al 1994). This will entail the construction of a suitable containment structure.

One of the major pressures on the integrity of a containment structure is erosion, causing landform instability, resulting in exposure of encapsulated contaminants, elevated sediment delivery at catchment outlets, and subsequent degradation of downstream water quality (Evans 2000). Erosion rates on containment structures can be quantified using 3-dimensional landform evolution simulation techniques (SIBERIA) (Willgoose et al 1991).

Vegetation generally reduces erosion and the effects should be quantified to enhance rehabilitation design at the Ranger mine. This has been done using large scale plot erosion (600 m^2) data from the waste rock dump to: (1) derive site-specific linear relationships between bedload and total sediment load; and (2) provide an understanding of the variation of sediment yield during the Wet season as site conditions change.

Methods

During the 1994/95 Wet season data (table 1) were obtained under natural rainfall events for two sites (soil and fire sites) on the waste rock dump at the Ranger Mine (fig 1). The sites were established in November 1994. The surface (average slope of 1.2%) of the soil site had been ripped and topsoil added approximately 8 years prior to this study and now had a vegetation cover of low shrubs and grasses (*Acacia* and *Sorghum* species). The surface of the fire site (average slope of 2.3%) was initially ripped and topsoil added, and was now vegetated with low shrubs, grasses and well established trees (*Eucalyptus*, *Acacia*, *Grevillea* species) approximately 10 years old. Both the soil and fire site had high levels of surface roughness due to the ripping and the presence of large, competent, rock fragments. Formation of debris dams also increased the surface roughness of both plots. A third site, the cap site, established in 1993, had an average slope of 2.8%, was not surface ripped, had negligible vegetation and a cover of fine surface material over a pan. This site had low surface roughness. Only rainfall, runoff and bedload data were collected on the cap site during the 1994/95 Wet season.

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1 A more detailed discussion of this research is provided in Saynor MJ & Evans KG 2001. Sediment loss from a mine waste rock dump, Northern Australia. *Australian Geographical Studies* 39(1), 34–51.

Table 1 Fire and soil site data, for monitored events during the 1994/95 Wet season. Cap site data from Evans (1997) are also shown.

Site	Date	Total rainfall (mm)	Maximum 10 minute rainfall intensity (mm h^{-1})	Total discharge (l)	Runoff coefficient	Suspended load (g) [Concentration (g L^{-1})]	Bedload (g) [Concentration (g L^{-1})]	Total load (g) [Concentration (g L^{-1})]
Fire	17/1/95	6.2	31	121.9	0.03	9.7 [0.08]	92.4 [0.76]	102.1 [0.84]
	19/1/95	12.8	50	356.1	0.05	40.3 [0.11]	98.6 [0.28]	138.9 [0.39]
	20/1/95	7.2	41	65.9	0.02	8.6 [0.13]	43.0 [0.65]	51.6 [0.78]
	25/1/95	44.4	128	1254.6	0.05	12.0 [0.01]	248.4 [0.20]	368.4 [0.29]
	10/2/95	20.4	59	440.0	0.04	35.3 [0.08]	38.4 [0.09]	73.7 [0.17]
	18/2/95	38.2	90	1383.9	0.06	69.6 [0.05]	438.4 [0.32]	508.0 [0.37]
	28/2/95	33.4	86	853.1	0.04	65.3 [0.08]	268.2 [0.31]	333.5 [0.39]
	1/3/95	14	44	128.4	0.02	16.2 [0.13]	107.2 [0.84]	123.4 [0.96]
	27/3/95	8	37	62.8	0.01	12.1 [0.19]	13.6 [0.22]	25.7 [0.41]
Soil	17/1/95	6.6	34	288	0.07	29.8 [0.10]	118.2 [0.41]	148.0 [0.51]
	19/1/95	18.4	68	1397	0.13	111.5 [0.08]	325.0 [0.23]	436.5 [0.31]
	20/1/95	9.8	56	596	0.10	58.5 [0.10]	556.1 [0.93]	614.6 [1.03]
	25/1/95	39.4	118	2303	0.10	251.3 [0.11]	889.7 [0.39]	1141 .0[50]
	27/1/95	7.4	37	269.1	0.06	19.0 [0.07]	85.8 [0.32]	104.8 [0.39]
	10/2/95	20.4	55	1142	0.09	89.4 [0.08]	277.8 [0.24]	366.4 [0.32]
	18/2/95	48.4	121	4020	0.14	676.2 [0.17]	1357.6 [0.34]	2033.8 [0.51]
	28/2/95	28	73	1805	0.11	298.5 [0.17]	327.0 [0.18]	625.5 [0.35]
	8/3/95	12.8	74	956.1	0.12	108.1 [0.11]	234.5 [0.25]	342.6 [0.36]
	27/3/95	8	42	241.8	0.05	27.1 [0.11]	58.1 [0.24]	85.2 [0.35]
Cap	16/11/93	18	54	6509	0.61	4440 [0.68]	6074 [0.93]	10514 [1.62]
	09/12/93	49	132	21638	0.75	18930 [0.88]	25007 [1.16]	43937 [2.03]
	10/12/93	11	30	4450	0.68	721 [0.16]	814 [0.18]	1535 [0.35]
	20/12/93	9	48	3013	0.57	611 [0.20]	2767 [0.92]	3377 [1.12]
	21/02/94	16	54	9988	1.06	1683 [0.17]	2914 [0.29]	4597 [0.46]

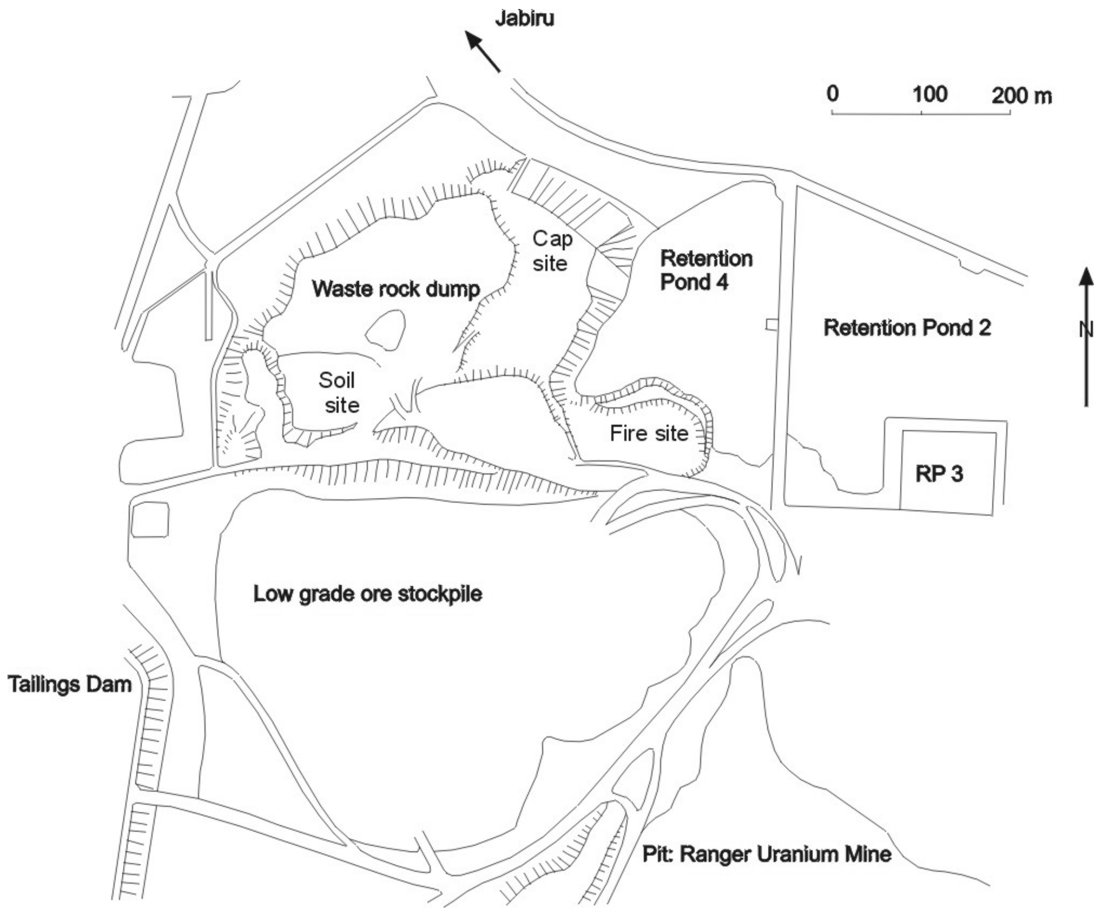

Figure 1 Location of the study sites at Ranger mine

A vegetation survey on the soil and fire sites commenced on 30/1/95 (R Hall pers comm, 1996). Representative 1 m^2 quadrants (randomly chosen) were pegged at four locations at each plot and fortnightly measurements of living ground cover (percentage and approximate mean grass heights) were made.

Bedload and total load relationships

There was a significant linear relationship between bedload and total sediment loss for both the soil and fire sites (fig 2). 1993/94 Wet season data from events observed on the cap site (Evans 1997) (table 1) also indicate a significant relationship between bedload and total sediment loss (fig 2). These relationships (fig 2) make it possible to predict the total sediment loss for a storm using collected measured bedload from the studied sites.

Bedload measurements were greatest from the unvegetated cap site and lowest from the densely vegetated fire site. The site-specific relationships between total sediment load and bedload indicate that the percentage of suspended sediment discharge from the plot decreases as the percentage plant cover increases. This may be due to a filtering effect by the vegetation. The power function

$$\text{total sediment loss} = 1.28 \times \text{bedload}^{1.02} \qquad (r^2 = 0.99,\ p<0.001) \qquad (1)$$

is applicable to all three sites. However, it under-predicted total sediment load during the two largest storms on the cap site (table 1) by approximately 14%. The cap site linear function (fig 2) over-predicted the event on 16/11/93 by 0.95% and under-predicted the event on 9/12/93 by 0.55%.

Generally, <20% of runoff events are responsible for >65% of total erosion losses (Edwards 1987, Wockner & Freebairn 1991, Erskine & Saynor 1996) making it important that high sediment loss events are well predicted. The site-specific linear equations (fig 2) are more appropriate than the power function for predicting total sediment load from bedload, particularly with respect to the larger, more damaging, events. Both the power function (eqn 1) and the fire site linear function (fig 2) under-predict sediment loss for small events. The magnitude of the sediment loss at the lower end compared with losses at the higher end, make under-prediction at the lower end much less significant than at the higher end for landform rehabilitation design.

Similar relationships have previously been derived for a site in the USA (Olyphant et al 1991). The relationships derived in this study, specific to a Northern Australian mine site, have important application in erosion modelling and monitoring, as outlined below.

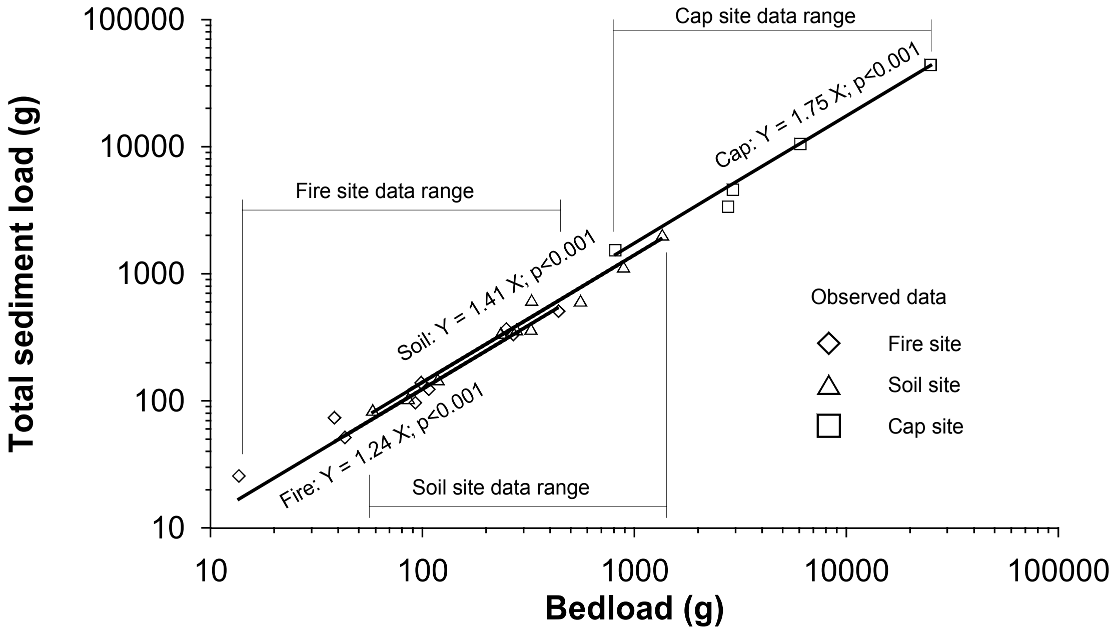

Figure 2 Fitted bedload — total sediment load relationship for the study sites and data ranges for the sites. Cap site data are from the 1993/94 Wet season (Source: Evans 1997).

Application to erosion modelling

The sediment discharge equation in the SIBERIA landform evolution model has been calibrated using a total sediment–total discharge relationship of the form:

$$T = \beta' \int Q^{m+1} dt \qquad (2)$$

where T = total sediment load (g), $\int Q^{m+1}\, dt$ = total discharge (L) and β' is a fitted parameter (Evans et al 1998). For this equation the total load, comprising the bedload collected at the end of an event and the total suspended load, derived through integration of sediment discharge (Q_s) (g s^{-1}), is fitted against $\int Q^{m+1}\, dt$. The exponent on Q, $(m+1)$ is fitted to each instantaneous discharge within the integral (Evans et al 1998). This may reduce the effect of the hysteresis identified in sediment discharge events as using total event data removes the temporal component within an event (Moliere et al 2002 — this volume).

Bedload is more easily collected than the suspended load. Therefore bedload - total sediment load relationships based on bedload can be used to extend the data set to fit equation 2 provided instantaneous discharge data are available. This is particularly important where high discharge event data are incomplete.

Application to erosion monitoring

The bedload–total sediment load relationships have application to monitoring specific parts of a mine site for sediment movement off-site, or for the design of sedimentation ponds. Using the type of erosion plots described here, intensive monitoring may only be needed in the initial years until the relationships can be established. After this period the relationships could be used to predict the amount of suspended load (generally the most mobile and potentially damaging to the environment) from the collected bedload. The power function (eqn 1) could reasonably be applied to any surface treatment on the Ranger mine landforms, provided allowance is made for under-prediction of the large runoff events.

Temporal sediment yield variations

The variation in bedload with time from the three sites is shown in figures 3B, C and D. For the fire and the soil sites the inverse log-linear relationships describing event bedload with time are significant (figs 3C & 3D). Initial bedload from the less vegetated soil site was almost twice that from the fire site which had the more complex vegetation community. Bedload from the soil site decreased with time at a greater rate than from the fire site but remained approximately constant for the unvegetated cap site. For all sites the scatter associated with the data is due to the size, duration and timing of the rainfall events.

Quadrant measurements (Hall pers comm 1996) showed a variable increase in total living ground vegetative cover from approximately 16% on 30/1/95 to 48% on 28/3/95 on the soil site and from 26% to 44% over the same time on the fire site. Living cover then decreased during dieback as the Wet season finished. The estimates of living cover are not a true estimate of total cover on the plots as there is a high percentage of leaf litter and dead vegetation present. Observations indicate this almost doubles the surface cover.

Event rainfall during the 1994/95 Wet season ranged from 7 mm to 178 mm. Rainfall events were selected to demonstrate the amount of rainfall and the associated bedload from the plots (figure 4). The three monitored plots were within 500 m of each other and it is reasonable to assume that the sites experienced the same storm events. For corresponding storms at each site, bedload was highest from the cap site. Bedload loss was higher for the soil site than for the fire site. Generally, bedload and rainfall amount are positively correlated.

There is probably a combination of two contributing factors to the reduction in bedload on the soil and fire sites: (1) a significant increase in vegetation cover during the early part of the Wet season; and (2) a possible depletion of erodible material, which was difficult to determine due to the lack of early Wet season sediment concentration data. Early Wet season rains may have eroded the sediment that might have been detached and made available during the preceding Dry season, resulting in an initial flush of sediment. Increasing vegetation cover during the Wet season coincided with a reducing bedload rate. Spear grass (*Sorghum*) were the dominant vegetation that grew during the Wet season. The dense cover of this genus contributed to sediment loss reduction.

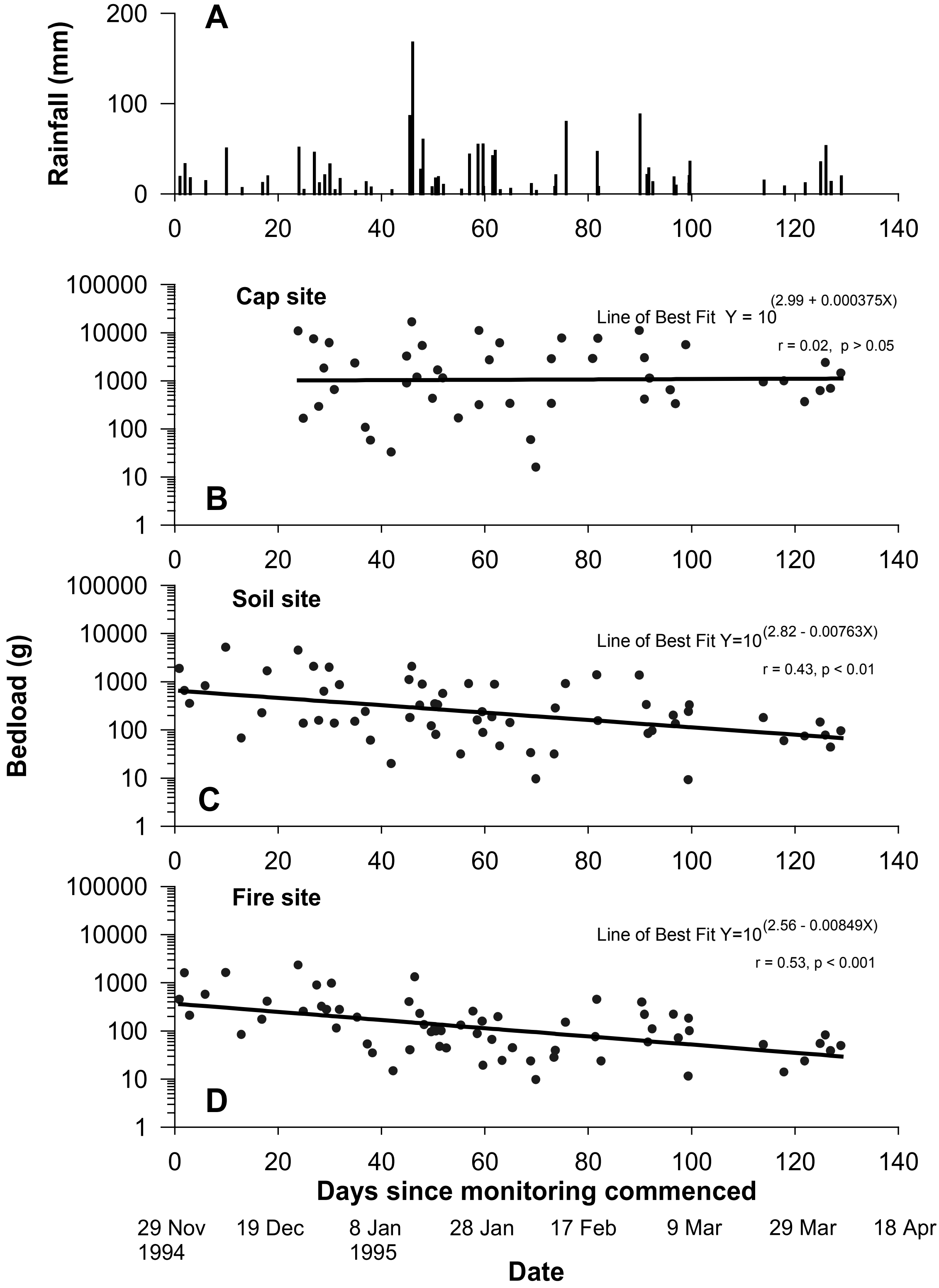

Figure 3 Bedload from the monitored sites and the corresponding rainfall

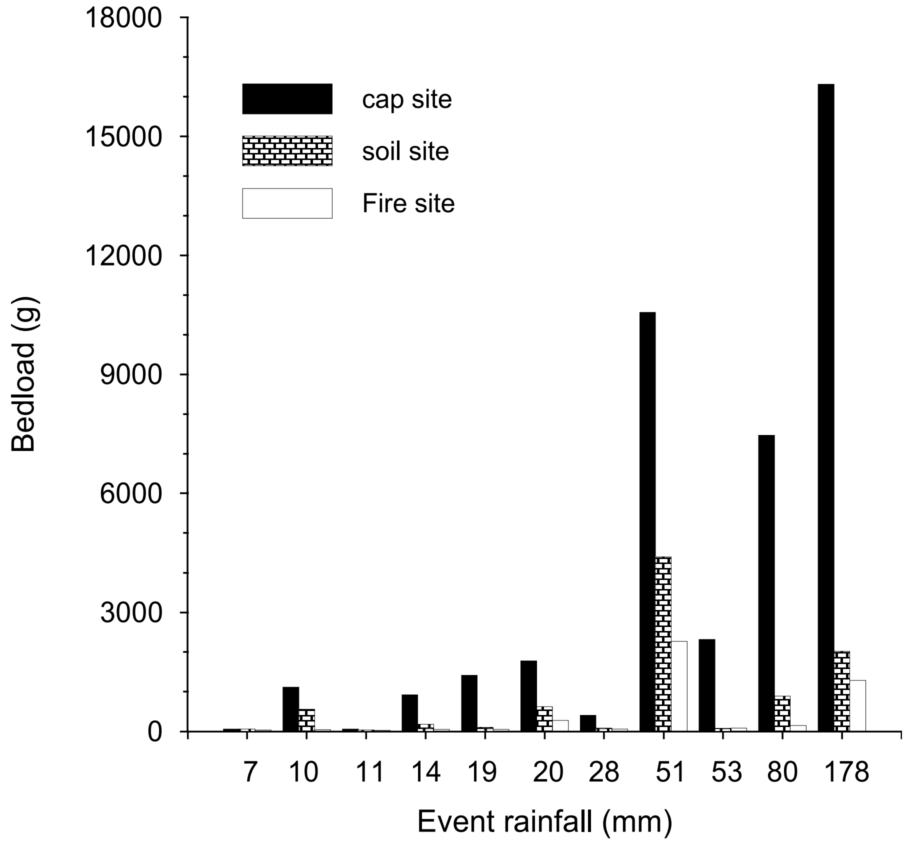

Figure 4 Bedload losses from selected rainfall events

Conclusions

The observed linear relationships between bedload and total sediment load have important implications for the derivation of modelling parameter values. In the case of the Ranger mine it is possible to collect the bedload sediment after the event and calculate the total load using the site specific sediment relationships. If sufficient storms are not observed, where suspended sediment load is measured, predicted total sediment loads could be used to calibrate landform evolution models such as SIBERIA.

The main change, occurring during the 1994/95 Wet season monitoring period, was an increase in low level vegetation cover on the soil and fire sites. Increasing vegetation cover by small shrubs and grasses (*Acacia* and *Sorghum* species) is a major factor controlling the observed reduction in sediment loss. Sediment loss from the vegetated plots reduced at a decreasing rate until reaching a practically constant rate midway through January. The results also show that the fire site with the established vegetation cover of taller trees had the least amount of bedload while the cap site with no vegetation had the greatest bedload.

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