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Development of a GIS based approach to mining risk assessment

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Executive summary

A GIS offers a means by which the data collected during the assessment of possible mining impacts can be stored and manipulated. A GIS that provides a central focus point for the storage, manipulation and retrieval of information generated by the investigation into the geomorphological impact of the ERA Jabiluka Mine has been developed. Implementing a flexible, GIS-centred approach to data management allows the data storage, manipulation and retrieval powers of GIS to be retained whilst maintaining access to the functionality contained within these other software packages. The GIS has also been linked to the DistFW hydrology model and SIBERIA landform evolution model, to provide a more spatial approach to assessing the impact of mining on the long-term landform evolution of a catchment.

A GIS based rapid erosion assessment method has been developed and evaluated. The method allows the user to quickly acquire and evaluate existing data to assist in the planning of more detailed monitoring, modelling and erosion assessment programs. The rapid erosion assessment method is based on a simplified version of the Revised Universal Soil Loss Equation (RUSLE), and allows the rapid parameterisation of the model from widely available land unit and elevation datasets. The rapid erosion assessment method is evaluated through the investigation of the effects of elevation data resolution on erosion predictions and field data validation.

More detailed, quantitative risk assessment can be conducted using a combination of landform evolution modelling and basin analysis in a GIS framework. SIBERIA has been parameterised using field data from Ngarradj* and applied to the catchment. Due to complexities of the catchment there were some difficulties with the hydrology component. However, the results indicate that SIBERIA is suitable and simulations showed little change in the catchment in the long term. Combining these with newly developed GIS tools to provide a geomorphometric basin analysis of the year 0 and year 1000 simulated catchments strengthens erosion risk impact assessment. The geomorphometric measures considered include the hypsometric curve, width function, cumulative area distribution and area-slope relationship.

Three areas have been identified as requiring further study in order to consolidate mining impact assessment: the incorporation of spatial variation in SIBERIA input parameters in the modelling process, an analysis of the sensitivity of the SIBERIA model to input parameter variations or error and the practical application of the GIS/modelling approach to assessing the impact of the ERA Jabiluka Mine on landform evolution in the Ngarradj catchment.

* Ngarradj is the Aboriginal name for the stream system referred to as Swift Creek.

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Note

A section of this report has been published elsewhere as a component of a journal article, but has been included here for completeness. Where referring to this section of the report, please refer to the journal article referenced below and not this report.

Section 3:

Boggs GS, Devonport CC, Evans KG & Puig P 2001. GIS-based rapid assessment of erosion risk in a small catchment in the wet/dry tropics of Australia. *Land Degradation and Development* 12 (5) (in press).

1 Introduction and background

1.1 Introduction

The impact of mining activities on complex and relatively poorly understood environments represents a significant issue facing decision-makers in northern Australia. The catchment of Ngarradj[1], a major right-bank tributary of the Ramsar-listed Magela Creek wetlands, will be the first catchment to be affected should any impact occur as a result of mining operations at the Energy Resources of Australia (ERA) Jabiluka Mine. The Ngarradj catchment covers areas both within and excised from the World Heritage listed Kakadu National Park, Northern Territory, Australia. In February 1999, a collaborative project between ***eriss*** and the Northern Territory University was established to develop a GIS that interacts with sediment transport, hydrology and landform evolution modelling techniques for use in the long-term assessment and management of the Ngarradj catchment (Boggs et al 1999). This report provides details of the development of the following GIS tools for geomorphological impact assessment: (i) a rapid erosion assessment technique; (ii) GIS-based landform evolution modelling; and (iii) basin analysis using geomorphometric measures. The tools are demonstrated by application to the Ngarradj catchment. The report also provides an outline on future research directions required to complete the project, providing a valuable tool for the assessment and management of mining impact.

1.2 Study area

The Ngarradj catchment is located approximately 230 km east of Darwin and approximately 20 km north of the town of Jabiru (fig 1). The Ngarradj catchment lies partly in the Jabiluka Mineral Lease (JML) and partly in the surrounding Kakadu National Park (KNP), and contains the ERA Jabiluka Mine site in its western section. The catchment is elongated with a length of approximately 11.5 km, a maximum width of approximately 7.5 km and a total area upstream from the most downstream gauging site of approximately 43.5 km^2 and a total area upstream of the confluence with Magela Creek of almost 67 km^2.

Within the catchment two distinct landform regions are represented — an upland plateau region with highly dissected sandstone and shallow sandy soils, and the Ngarradj floodplain with deep sandy soils. Located within the monsoon tropics climatic zone, the catchment experiences a distinct Wet season from October to April and Dry season for the remainder of the year. The average annual rainfall at Jabiru is approximately 1483 mm (Bureau of Meteorology 1999), and is associated with low frequency and intensity monsoonal events and high intensity storm events, with rainfall intensities of 100 mm/hr and a duration of 10 minutes expected to occur annually (Finnegan 1993).

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[1] *Ngarradj* is the Aboriginal name for the stream system referred to as 'Swift Creek' in earlier documents. Ngarradj means sulphur crested cockatoo. The full term is Ngarradj Warde Djobkeng. The literal translation is 'cockatoo vomited on rock', indicating the creek's genesis (and ultimately the creek line) and is just one of several dreaming (Djang) sites on or adjacent to the Jabiluka mineral lease (A Ralph pers comm 2000).

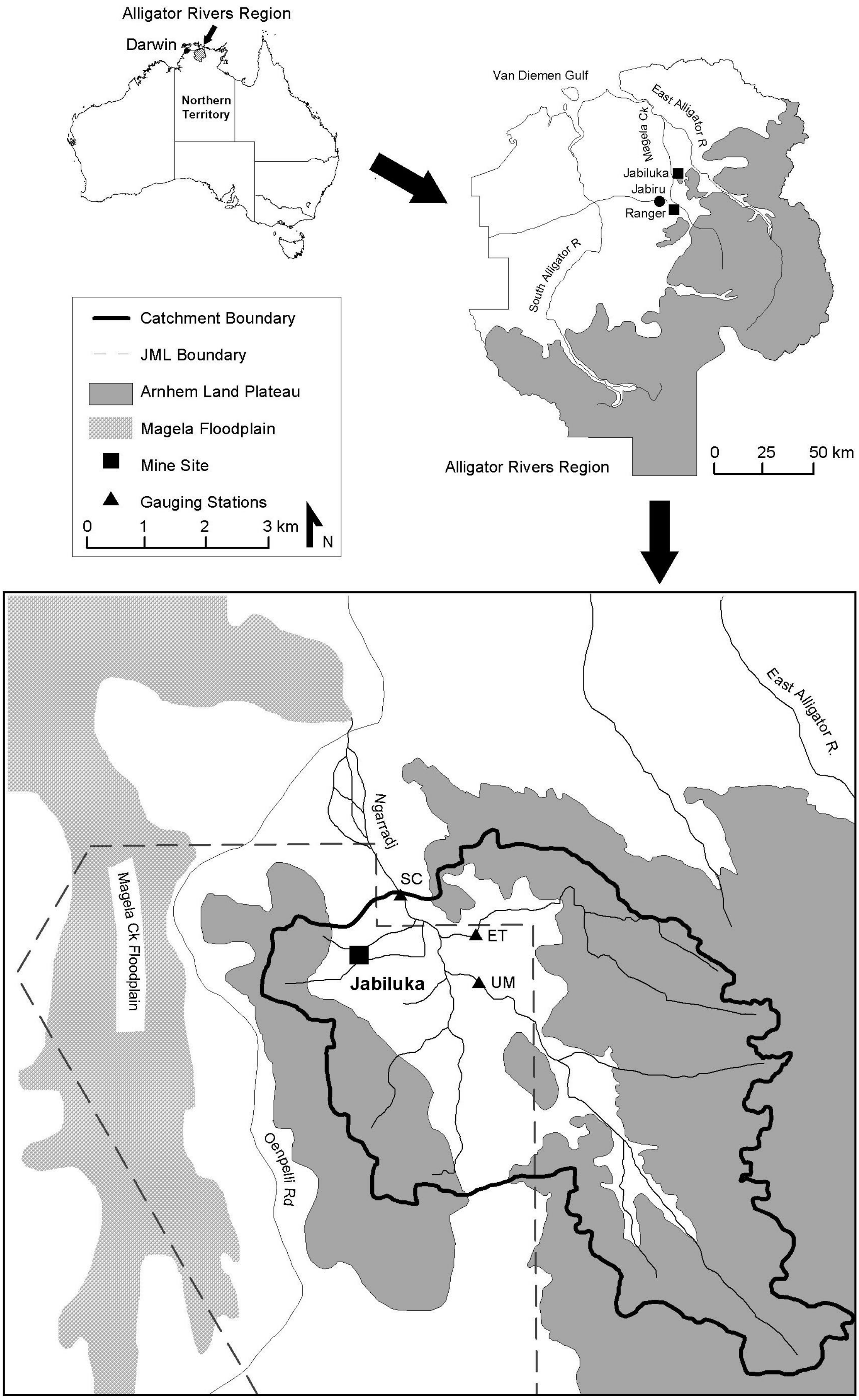

Figure 1 Location of the Ngarradj catchment in the Northern Territory of Australia where ET = East Tributary, UM = Upper Main and SC = Swift Creek

1.3 Background

The design of mine layouts primarily attempts to optimise operations, minimise costs and maximise resource recovery (Jeffreys et al 1986). However, increasing public awareness and stricter enforcement of regulatory requirements for rehabilitation of sites following mining have made environmental planning an essential part of mine planning (Evans et al 1998). A significant impact of mine sites on the environment involves the pollution of waterways through erosion of post-mining landforms and movement of the sediment into streams and rivers (Evans 2000). Computer modelling of geomorphic processes of mining affected catchments, with particular evaluation of the degradation of the engineered landforms, is a crucial aspect of the assessment program (Willgoose & Riley 1998). A considerable body of research exists that addresses the application of hydrological, erosion and topographic evolution modelling to mine site rehabilitation (Pickup et al 1987, Silburn et al 1990, Evans et al 1998, West & Wali 1999).

Environmental models attempt to realistically simulate spatially-distributed, time-dependent environmental processes (Steyaert 1993). GIS, through its ability to capture, manipulate, process and display geo-referenced data, is able to describe the spatial environment. GIS and environmental modelling are therefore synergistic, with the overlap and relationship between these technologies being clearly apparent (Fedra 1993). However, GIS and environmental modelling have evolved separately, and thus have different data structures, functions and methods for inputting and outputting spatial information (Maidment 1996). Integrating GIS with geomorphological models will provide a valuable tool for assessing and managing the impact of mine site landform degradation on landform stability and catchment erosion and hydrological processes.

1.3.1 Erosion hazard models

Erosion hazard models provide a simple and efficient means for investigating the physical processes and mechanisms governing soil erosion rates and amounts. Erosion hazard models are cost-effective and time-efficient as they are designed to take advantage of widely available, relatively inexpensive datasets. However, these models commonly do not provide a quantitative measure of erosion, but rather produce a spatially distributed, dimensionless index of erosion risk. Erosion hazard models can be used for farm planning, site-specific assessment, project evaluation and planning, policy decisions or as research tools to study processes and the behaviour of hydrologic and erosion systems (DeCoursey 1985). Many erosion hazard models are primarily based on the topographic analysis of digital elevation data (Wilson & Gallant 1996, Prosser & Abernethy 1999). The topographic factors considered within these models are most simply calculated as a function of upslope contributing area and local slope. The Revised Universal Soil Loss Equation (RUSLE) LS factor and the unit stream power based topographic factor are two commonly used, more complex methods for estimating the effect of topography on erosion potential. These models are therefore very dependent on the resolution and accuracy of the digital elevation data (Mitasova et al 1996).

Erosion hazard models are distributed models that depend on the input of spatial datasets from a variety of sources. GIS offers a means for integrating these spatial datasets whilst also providing tools for implementing erosion hazard models. Erosion hazard models are therefore often ‘embedded’ within a GIS, with the model’s functions essentially becoming part of the functionality of the GIS (Loague & Corwin 1998). This approach is the tightest and most complex method for integrating GIS and environmental models and is therefore most easily and commonly implemented when integrating relatively simple models and GIS. The coupling of software components in embedded systems occurs within a single application with shared memory, as opposed to simply having a shared database and a common interface.

1.3.2 Landform evolution models

Prediction of the future evolution of landforms is one of geomorphology's primary research goals. This necessitates the study and modelling of erosion, sediment transport and deposition processes that control the long-term geomorphological development of a formed surface (Evans et al 1998). Landform evolution models therefore differ significantly from the previously described soil erosion hazard models as they quantify the erosion and deposition occurring within a catchment. However, topographic evolution models extend soil erosion models by using a continuity equation to model aggradation, where more material enters an area than is removed, as well as areas of net erosion (Kirkby 1971). This process is applied iteratively using a previously assigned time interval, therefore showing the progressive evolution of the landscape (Howard 1994).

SIBERIA is a computer model designed for examining the erosional development of catchments and their channel networks (fig 2) (Willgoose et al 1989). The model incorporates the interaction between hillslopes and the growing channel network based on physically observable mechanisms. Catchment elevations, including both hillslopes and channels, are simulated by a mass transport continuity equation applied over geologic time (Willgoose & Riley 1998). An explicit differentiation is made between the processes that act on the hillslope and those acting within the channel network. Channels are dominated by fluvial erosion processes whilst hillslopes are shaped by both fluvial and diffusive processes. Channel network growth is controlled within the model by a physically based threshold mechanism. That is, if a channel initiation function (based on slope and discharge) exceeds some predetermined threshold (dependent on local resistance to channelisation), then channel head advancement occurs. Interaction between the elevations on the hillslopes and the growing channel network occurs through the different transport processes in each regime and the resultant preferred drainage to the channels. It is the interaction of these processes which produces the long-term catchment form (Willgoose & Riley 1998). Topographic change is represented on the DEM by changes in node elevation due to sediment import from upstream grid cells and sediment export to downstream grid cells.

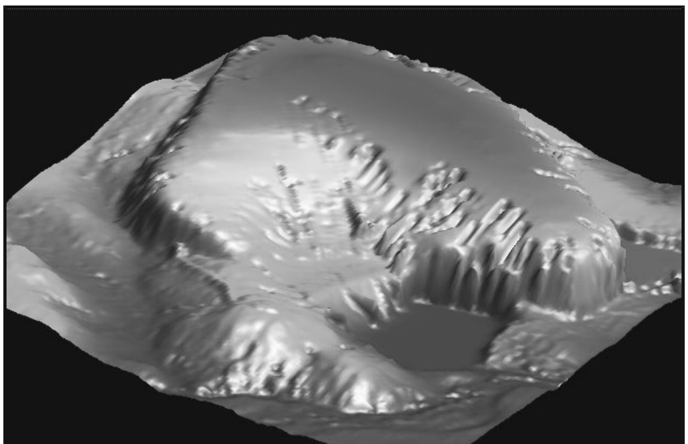

Figure 2 Modelled landform evolution on a proposed post-mining landform, showing the development of gullies and depositional fans (after Evans 1997)

Calibration of the SIBERIA landform evolution model involves deriving parameters using a sediment transport equation and hydrology model. In addition to these parameters, it is necessary to derive long-term average SIBERIA model parameters for the landform being modelled. This complex process, as described by Willgoose and Riley (1993), is essentially composed of three parts including: 1) yielding the temporal average discharge area relationship; 2) calculation of the runoff series and long-term sediment loss rate; and 3) application of a slope correction function.

Linking SIBERIA to a GIS will facilitate a more spatially aware approach to assessing mining impact on the long-term landform evolution of the catchment. Providing GIS based tools for incorporating spatial variability in the SIBERIA modelling process will provide a more efficient method for assessing alternative management practices as input maps can be rapidly modified to allow the simulation of alternative scenarios (De Roo 1996). The method proposed to integrate the SIBERIA landform evolution model with a GIS is termed 'tight coupling'. Tight coupling involves the deeper integration of GIS and environmental models characteristically by providing a common user interface for both the GIS and the model. This tight coupling of the GIS and the model means that the file or information sharing between the respective components is transparent to the end user (fig 3) (Loague & Corwin 1998). A tightly coupled model and the GIS must share the same database. There are various methods to implement this approach. The use of a higher-level application language or application generator built into the GIS represents one feasible way. An alternative is the use of tool kits that accommodate both GIS functionality as well as interface components for simulation models and, as an extreme measure, the approach can be implemented through assembler programming (Fedra 1993). The tight coupling approach commonly involves savings in time and expense, but requires expertise from the user and relies on the GIS to be adequate for data handling (Charnock et al 1996). An eventual environment to facilitate the tight coupling of GIS, models and other applications is described by Lam et al (1996) as one in which a toolkit exists that connects components smoothly and for which a user selects only those tool groupings which are needed for the task at hand and for which external applications can be attached in an orderly fashion by an end user.

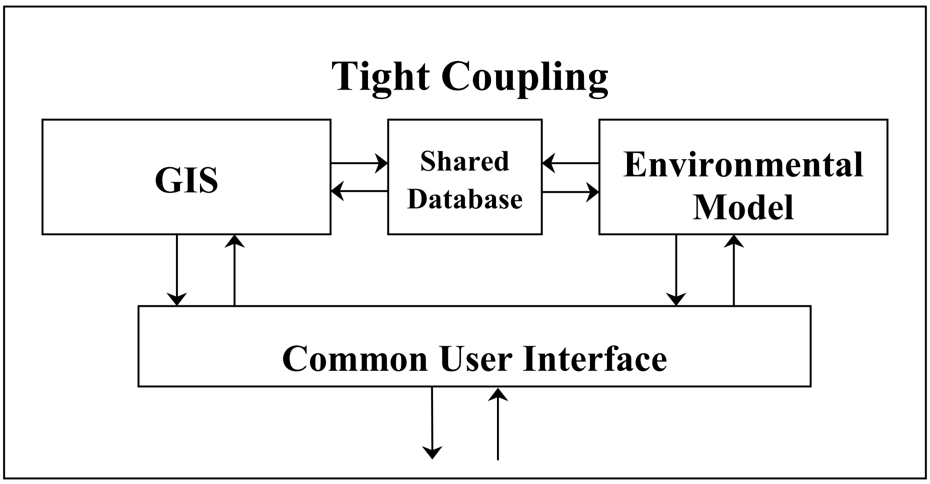

Figure 3 A conceptual diagram of the tight coupling approach to model/GIS integration (after Fedra 1993)

1.3.3 Basin analysis with GIS

1.3.3.1 Preparation of DEMs

Basin physiographic characteristics have long been recognised as important indices of surface processes (Horton 1945, Strahler 1957). Such parameters have been used in various studies of geomorphology and surface-water hydrology including the prediction of flood characteristics, sediment yield and the evolution of basin morphology. However, basin analysis has been known to be tedious and labour intensive as most measurements are made manually on large to medium scale topographic maps. Any attempt to measure more complex parameters than elevation and relief, such as stream length, drainage density, mean basin elevation and slope and channel gradient for streams of different orders, was always hampered by the amount of work an analyst had to endure (Wang & Yin 1998). The increased popularity of GIS technology and availability of Digital Elevation Models (DEMs) has led to wide recognition of the potential of using DEMs in studies of surface process (Wharton 1994). DEMs are rectangular grids of evenly spaced terrain heights generated from spot height data, contour data, scanned aerial photographs or satellite imagery. DEMs, through the development of new methods and algorithms, allow the extraction of terrain and drainage features to be fully automated. DEMs have been used to delineate drainage networks and watershed boundaries, to calculate slope characteristics and to produce flow paths of surface runoff (Moore et al 1991, Quinn et al 1992). DEMs have also been incorporated in many erosion, non-point source pollution and hydrologic models. However, to use DEMs efficiently and appropriately the optimum cell size, or resolution, must be chosen. Resolution is among the most important DEM attributes and will determine the usefulness and cost of a DEM.

DEMs are commonly used for automating the watershed boundary and stream network delineation process. However, studies have shown that the use of raster data sets for watershed boundary and stream network delineation can produce stream networks that are inconsistent with previously accepted vector representations (Saunders & Maidment 1995, Mizgalewicz & Maidment 1996). These inconsistencies can be attributed to problems of map scale and the lack of adequate DEM vertical resolution in areas of low relief (Saunders 2000). ‘Stream burning’ is a method by which the problem of stream network replication can be resolved and involves integrating vector hydrography data layers into the DEM prior to watershed boundary or stream network delineation. More specifically, the process of stream burning involves forcing flow within a DEM through the grid cells corresponding to the stream line network by directly modifying the elevation values of grid node points along the stream line relative to the surrounding areas. However, the process requires the selection of a vector hydrography layer at a similar scale as the DEM that has been extensively preprocessed before being ‘burnt in’. Stream burning can also introduce artificial parallel streams (Hellweger 1997) into the drainage network as well as distorting watershed boundaries delineated from the burned DEM. Various DEM adjustment methodologies have been developed to address some of these anomalies.

1.3.3.2 Standard GIS basin analysis tools

Many GIS software packages provide standard tools for basin analysis. These tools implement raster geoprocessing operations as point, neighbourhood or zonal analyses. Raster geoprocessing creates new datasets by altering pre-existing data (eg elevation data) to derive new datasets (slope data). Point operations, often referred to as map or grid algebra, create new datasets by calculating new values for a grid on a cell-by-cell basis (Delaney 1999). The most conceptually simple form of math algebra involves grid layers that directly overlay each other. Point functions can be grouped into those functions that operate on a single input grid theme ('mathematical functions') and those that apply a mathematical operation to the values in two or more input grid themes ('mathematical operators'). Mathematical functions apply logarithmic, arithmetic, trigonometric and power functions to the value in each grid cell. Mathematical operators, on the other hand, consist of arithmetic or conditional statements. Arithmetic statements combine grid layers though addition, subtraction, multiplication or division. For example, an arithmetic function of the form:

grid1 – grid2 = grid3

can be used in a landform evolution study to determine modelled elevation changes (grid3) between an output elevation grid after 1000 years (grid1) and an initial elevation grid (grid2).

Conditional statements use rules to ascertain whether a particular state or condition is true or false. Conditional statements are generally composed of boolean (AND, NOT and OR) or relational (eg greater than, less than, equal to) operators that define how one grid relates to another. Queries are processed within a GIS by the sequential examination of a grid and the placement of unique numbers in each cell to define true and false responses (often 1 for true, 2 for false) (Delaney 1999). For example, when examining the elevation change grid in the above example, a relational operator can be used to determine the areas of net erosion:

grid3 < grid4

where grid4 is a grid in which each cell is equal to 0.

Many standard basin analysis functions, such as the definition of slope, drainage direction and flow accumulation, are based on neighbourhood operations. Neighbourhood operations examine a target cell and the area surrounding it in order to define the value in the new dataset for the corresponding cell. The neighbourhood size (3×3 cells, 3×5 cells) and shape (eg square, rectangular, circular) can be defined by the user. For each cell in an input grid theme, the neighbourhood analysis functions compute a statistic such as the majority, maximum, standard deviation etc. These statistics can then be used to achieve higher order analyses. For example, the calculation of slope involves finding the maximum change in elevation between the target cell and surrounding cells. This value is then divided by the length over which the elevation change occurs, and slope is finally calculated as the inverse tan of this number. Neighbourhood functions are also used to filter a dataset in order to either smooth irregularities from the dataset (low pass filters) or highlight areas (high pass filters) of difference.

Zonal analyses implement similar geoprocessing operations to the functions offered within a neighbourhood analysis. However, zonal analyses calculated the statistics in a zonal context and hence require two input grids. One grid defines the zones for which each statistic will be calculated, where each zone has a unique number. The second contains the data of interest. The resultant value from the statistical operation is subsequently placed in each cell of that zone to produce the new dataset.

1.3.3.3 Geomorphometric measures for assessing catchment change

Geomorphometry, defined as the 'quantitative treatment of the morphology of landforms' (Morisawa 1988), has expanded significantly since the studies of Horton (1945) and Strahler (1964). 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 algorithms 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 (Perera 1997). These descriptors have also been successfully used to quantify and compare SIBERIA derived landscapes with natural landscapes (Hancock et al 2000a). This study represents the first attempt to apply these measures to assessing the impact of mining on catchment evolution.

Hypsometric curve

The hypsometric curve, or cumulative distribution curve, is defined as the area above a given elevation in a catchment divided by the total area of the catchment, plotted against the elevation of the point divided by the relief of the catchment. The hypsometric curve therefore provides a method for analysing the geomorphic form of catchments and landforms by characterising the distribution of elevation within a catchment (Willgoose & Hancock 1998). The shape of the hypsometric curve has also been linked to the age of the catchment. Strahler (1957, 1964) recognised three distinct landform developmental stages that can be identified using the hypsometric curve including young, mature and monadnock. The hypsometric curve is therefore an important tool when analysing landform evolution over geologic time scales.

Width function

The width function is a geomorphic descriptor that describes channel development and provides a good estimation of hydrologic response since it is strongly correlated with the instantaneous unit hydrograph. The width function is generally calculated as the number of channels at successive distances away from the basin outlet as measured along the network (Surkan 1968). However, various other forms of the width function have been presented including the normalised width function (Mesa & Mifflin 1986), standardised width function (Naden 1992) and a simplified form of the width function (Hancock 1997). The width function can be relatively easily derived from a DEM, but generally requires the prior definition of a stream network. The simplified form of the width function adopted by Hancock (1997) eliminates the need to derive a stream network by defining the width function as the number of drainage paths (whether they be channel or hillslope) at a given distance from the outlet. The traditional form and simplified form of the width function will be adapted for implementation within a GIS and evaluated through application to the Ngarradj catchment.

Cumulative area distribution

The cumulative area distribution has been used as a means of characterising the flow aggregation structure of channel networks (Rodriguez et al 1992) and in the calibration of geomorphological models (Moglen & Bras 1994, Sun et al 1994). The cumulative area distribution, calculated as the area of the catchment that has a drainage area greater than or equal to a specified drainage area, is an important component in determining what sections of a catchment are saturated (Perera & Willgoose 1998). This has important implications for determination of the maximum runoff rate during rainfall events and what area of a catchment can evaporate at the maximum rate between rainfall events (Hancock 1997).

Area-slope relationship

The area-slope relationship relates the area draining through a point (A) to the slope at the point (S). The area-slope relationship has been shown to be a fundamental geomorphic relationship showing information concerning the dominance of both diffusive and fluvial transport (Moglen & Bras 1994, Willgoose et al 1991). The area-slope relationship for a catchment has been reported by many authors as having the form:

$$A^{\alpha}S = \text{constant}$$

where the value of α was found to fall between 0.4 and 0.7 (Hack 1957, Flint 1974). The area-slope relationship has also been shown to be an effective method for comparing the elevation properties of different catchments.

2 GIS establishment

2.1 Introduction

A geographic information system (GIS) is being developed for the storage, retrieval and analysis of information generated by an investigation into the long-term geomorphological impacts of the Energy Resources of Australia (ERA) Jabiluka Mine. GIS are commonly linked with erosion and hydrology models (eg De Roo 1998, Haan & Storm 1996) but not often used in geomorphological impact assessment (eg Patrono et al 1995, Verstappen 1995). This study adopts a GIS-centred approach to the management and manipulation of data generated by a geomorphological impact assessment. Benefits of this approach include the simplification of data maintenance, revision and update, as well as facilitating availability and access for users. The aims are to simplify data analysis and presentation, to increase individual and group productivity and cost-effectiveness, and to provide an information system that could be integrated with other specialised fields in use within ***eriss***.

The methods and processes required to store, retrieve and manipulate the datasets resulting from impact assessment, range from spreadsheets and statistical analysis to spatial databases and visual analysis. Data emanating from the impact assessment that will be used in this project can be grouped into four categories, based on these methods and processes: (1) High Temporal Resolution Spreadsheet Data; (2) Raster Data; (3) Vector Data; and (4) Model Data. This requires the customisation of the GIS software package (ArcView®) through the development of specific GIS tools that allow the end user to interact with this range of data successfully. The GIS therefore provides a focal point for these datasets, retaining the flexibility and functionality required to store and manipulate each dataset, whilst offering a central link for the projects data (fig 4).

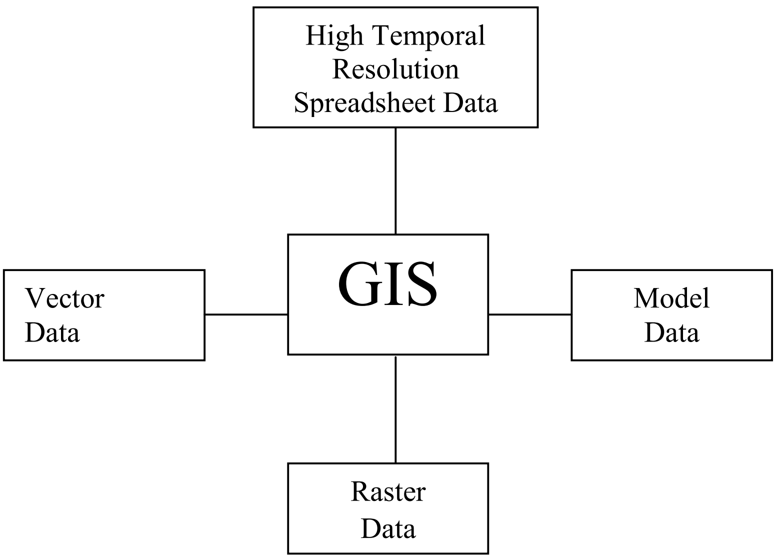

Figure 4 The approach used in the development of a GIS as a focal point for datasets generated during the geomorphologic impact assessment of the ERA Jabiluka Mine

2.2 High temporal resolution data

In November 1998 three stream gauging stations were established by ***eriss*** within the Ngarradj catchment (fig 1). Two stations are located upstream of all mine influences (on the main right bank tributary of Ngarradj ('East Tributary') and on the main Ngarradj channel ('Upper Main')). The third station ('Swift Creek') is located on the main Ngarradj channel downstream of the mine site and can be used to assess possible impacts from the mine site (fig 1). Data are collected from these stations at frequent intervals. Turbidity, rainfall and water level information is collected by each station at 6 minute intervals. Suspended sediment concentrations, electrical conductivity, pH and turbidity samples are collected by automatic samplers that are triggered by rises and falls in stream water levels, as predetermined for each station. It is possible to collect 24 samples at the upstream gauging stations East Tributary and Upper Main and up to 48 samples at the downstream Swift Creek site. In-stream velocity gaugings are conducted during each weekly site visit. Bedload movement information, collected using a Helley-Smith sampler according to the technique described by Emmett (1980), is also obtained during these visits. These data are used in this project to establish a discharge area relationship and to derive a sediment transport equation for the eventual calibration of the SIBERIA landform evolution model (see chapter 4).

The approach adopted to store, manage and retrieve these data involves customisation of the ArcView® GIS package to connect the GIS with relational database and spreadsheet software packages. Data collected during field visits or through laboratory analyses are entered as separate tables into a database through 'user-friendly' forms accessed through the GIS interface. All tables have a unique code that links them to a further table that contains descriptions of each gauging site and their geographic coordinates. A connection known as an Open Database Connectivity (ODBC) has been established between the GIS and database to enable data to be retrieved through customised dialog boxes embedded within the GIS interface using structured query language (SQL). Customisation of the GIS also allows the user to interactively select a site on the computer screen and interact with the associated databases, importing and graphing data for the selected site. This allows rapid assessment of temporal and spatial trends in the data. The data accessed by this more generalised toolbox include low temporal resolution spreadsheet data and image data, as well as high temporal resolution spreadsheet 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 allows the user to export data directly from the database to a spreadsheet package, allowing further statistical analysis and more sophisticated graphing operations.

2.3 Raster data

Raster data obtained for the Ngarradj project comprise a DEM constructed from 1:30 000 pre-mining (1991), aerial photography and remotely sensed imagery (including aerial photography, Landsat TM and MSS imagery). Raster data sets are generally composed of large amounts of data and thus require large and well-organised databases as well as 'user-friendly' data processing hardware and software. A GIS offers a highly suitable approach for efficient storage, retrieval and analysis of large raster data sets (Schultz 1993).

One of the great advantages of using DEM and remotely sensed data in hydrological and geomorphological studies is that more spatially variable information can be obtained, as opposed to the more common point data (eg rain gauges) (Schultz 1993). The DEM constructed for this project covers the Ngarradj catchment. Raster processing of DEMs using functions that are often in-built in a GIS, allows the user to obtain many derivatives of DEMs such as slope, aspect, convexity/concavity etc (Delaney 1999). Remotely sensed imagery, on the other hand, is considered to be a rapid and flexible method for obtaining updated data, particularly as images are easily stored and interpreted in a GIS (Al-Ankary 1991). Maintaining a GIS as the central data management system allows DEM and remote sensing derived data to be directly linked to data emanating from the other four categories of data shown in figure 4. Raster data, therefore, are useful in the examination and explanation of the high temporal resolution spreadsheet data and provide direct inputs into the hydrology and landform evolution models. Further analysis, including detailed geomorphometric analysis of the modelled output DEM within the GIS, will enable temporal and spatial variations in mining impacts on landform evolution to be detected.

2.4 Vector (dGPS) data

The ability of GIS to store and analyse vector data represents one of the prime reasons for the high level of attention paid to GIS over the past 30 years (Lam & Swayne 1993). The vector database established for ***eriss*** chiefly consists 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, from aerial photography or other imagery (Bull 2001). As much of these base vector data are too coarse for investigations at the Jabiluka project scale, the primary vector data source is from DEM/remote sensing derived products and differential global positioning system (dGPS) acquired data.

Many public and private agencies involved in the environmental impact assessment process are turning to GPS and GIS technologies to deliver precision at an acceptable cost and a refined database essential to the assessment of environmental impacts (Rodbell 1993). Differential GPS provide 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). dGPS, along with aerial photography interpretation, has been successfully used in initial channel reach characterisation and geomorphic mapping of the Ngarradj catchment. Characterisation of the catchment will enable the identification of sites most likely to be affected by mining impact and should facilitate the detection of possible geomorphologic imbalances resulting from mining activities at Jabiluka. Differential GPS information has also been collected on knick-point migration rates. GIS analysis of these snapshot datasets will provide vital information on quantifying mining impact on gully formation and extension rates. The use of dGPS to geo-reference field sites is considered crucial to the GIS-centred data management approach as all data are linked to a spatial location, facilitating the incorporation of all field project data into the information management system.

2.5 Geomorphological modelling with GIS

GIS and environmental modelling are considered to be highly complementary with both technologies attempting to analyse spatially distributed and time dependent objects and processes (Fedra 1993). However, since GIS and environmental modelling have evolved separately they have different data structures, functions and methods for inputting and outputting spatial information (Maidment 1993). Over the past two decades there has been considerable research into the integration of these two technologies to the extent that the synthesis of spatial data representations and environmental models has been described as the new ‘Holy Grail’ (Raper & Livingstone 1996). Currently there exist many different approaches to linking environmental models with GIS, from the very simple, in which the GIS is used for writing model input and the analysis of model output, to closely integrated systems (Charnock et al 1996).

Currently three environmental models are employed by ***eriss*** 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 of the form:

$$T = K \int Q^{m_1}\, dt \; \eta \qquad (1)$$

where T = total sediment loss, $\int Q^{m_1}\, dt$ = cumulative runoff over the duration of the event (Q = discharge (l s^{-1})) and K and m_1 are fitted parameters. $\eta \approx N(1, \sigma)$ is an independent multiplicative log-normally distributed error with mean 1 and standard deviation σ.

This model 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.

2.5.1 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 (De Vantier & Feldman 1993). The use of GIS in hydrologic analysis provides an effective method for the construction of spatial data and the integration of spatial model layers (Singh & Fiorentino 1996). GIS are able to generate both the topographic and topologic inputs required to accurately model hydrologic systems. GIS can also assist in design, calibration, modification and comparison of models. However, the acquisition and compilation of information required by a GIS for hydrological modelling is often labour intensive and is an issue commonly encountered in hydrologic applications of GIS (Hill et al 1987). 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 being composed of a number of sub-catchments for which information must be derived describing their horizontal shape, vertical relief, conveyance and flow relationships existing between the sub-catchments (table 12). A significant challenge in this research project has been to develop a set of customised tools that automatically generates this information 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. A description of the tools developed for the derivation of the required DistFW inputs is shown in table 1.

Table 1 Descriptions of the tools developed to facilitate the automatic generation of the topographic input requirements of the DistFW hydrology model

GIS tool	Function/DistFW topographic input requirement
Incidence	Calculates the flow relationships between sub-catchments. Directly determines 'maximum number of upslope sub-catchments' and 'sub-catchment incidence' for DistFWs.
Catchment width	Determines the average catchment width perpendicular to the central stream channel. Directly determines 'sub-catchment conveyance' values for DistFW.
Stream length	Computes the length of a catchment based on the central drainage channel. Directly determines 'the sub-catchment length' values for DistFW.
Min-max area	Calculates the minimum elevation, maximum elevation and area of each sub-catchment within the catchment being studied. Directly inputs 'UpSlope Elevation', 'DownSlope Elevation' and Sub-Catchment Area for DistFW.
Multi-point watershed	Generates a grid of multiple watersheds. Where one point is downstream of another, the intervening sub-catchment is automatically calculated.
Downstream	Reduces the area of a sub-catchment where one sub-catchment is downstream of another to the intervening area.

2.5.2 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. The SIBERIA landform evolution model is computationally intensive and consequently does not lend itself to interactive use. Integration of this model with a GIS will therefore attempt to increase the 'user-friendliness' of the model, whilst also extending the functionality of the model. The complexity of the model means that integrating the two technologies using an 'embedded' approach is not feasible. However, by using a tightly coupled approach the two technologies will essentially remain separate but will share a user friendly front-end and database. Furthermore, by using this approach the powerful processing and analytical capabilities of the GIS will be available for the analysis of SIBERIA output.

The suite of tools developed to link SIBERIA with the ArcView® GIS package has 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 is currently still a prototype under development. As such, only a brief description of the functionality contained in ArcEvolve will be provided in this report, with more detailed descriptions and applications to be published in the future as ArcEvolve is fully tested.

ArcEvolve adds two menus to the ArcView® 'View' document graphical user interface (GUI). The first, 'SIBERIA', contains a number of items that: (i) allow SIBERIA native format files to be imported and exported; (ii) provide access to dialog boxes for the creation and management of a SIBERIA parameter database; and (iii) run the model. A description of the items contained in this menu is provided in table 2.

Table 2 Descriptions of the menu items added to the ArcView® 'View' GUI, under the menu 'Siberia', when using the ArcEvolve extension for interacting with the SIBERIA landform evolution model

Menu item	Function description
	'Siberia'
Export to RST2	Exports ArcView® grids, with relevant parameters from database, to SIBERIA RST2 File format
Import RST2 grid only	Imports the digital elevation data only from a SIBERIA RST2 file into an ArcView® grid
Import All RST2 File	Imports the digital elevation data and parameter values contained in a SIBERIA RST2 file into and ArcView® grid and database respectively
Create boundary file	Creates a SIBERIA boundary file from an ArcView® grid
Import boundary rile	Imports a SIBERIA boundary file into an ArcView® grid
Create database	Creates a SIBERIA parameter database. The database contains an item 'gridname' that links each record to a grid.
Edit database	Opens the first of a series of nine dialog boxes that provide a user-friendly front-end for updating the parameter database for a selected grid
Copy parameters	Copies the parameters associated with one grid to a record associated with the selected grid
Delete parameters	Deletes a record from the parameter database
Run Siberia	Runs the SIBERIA model, with output imported into ArcView® following the completion of the model run

The second menu, 'Geomorph', contains functionality for the geomorphometric analysis of digital elevation data (the primary input and output of SIBERIA). Geomorphometry provides an effective means for quantifying changes in basin morphology and has been used in previous studies to assess the ability of SIBERIA to model landform evolution. The standard geomorphic statistics used in these studies have been the width function, hypsometric curve, cumulative area diagram and area-slope relationship. These statistics have been adapted for implementation within the ArcView® GIS package and have been included in the Geomorph menu of ArcEvolve (table 3).

Table 3 Descriptions of the menu items added to the ArcView® 'View' GUI, under the menu 'Geomorph', when using the ArcEvolve extension for interacting with the SIBERIA landform evolution model

Menu item	Function description
	'Geomorph'
Width function	Calculates the width function from a DEM, Flow Direction or Flow Accumulation grid. The width function allows the user to define the minimum drainage area required to form a stream (ie allows for both traditional and simplified calculation of width function). The output is line graph. The table is also available for exporting to more advanced graphical packages.
Hypsometric curve	Calculates the hypsometric curve from a DEM. The table is also available for exporting to more advanced graphical packages. The output is a line graph showing the hypsometric curve. The table is also available for exporting to more advanced graphical packages.
Cumulative area diagram	Calculates the cumulative area diagram from a DEM, Flow Direction or Flow Accumulation grid. The output is a line graph. The table is also available for exporting to more advanced graphical packages.
Area-slope relationship	Calculates the area-slope relationship from a DEM grid. The output is displayed as a log-log scatter graph. The table is also available for exporting to more advanced graphical packages.
Cut-fill	Adapted from the standard ArcView® 3D-Analyst tool that calculates the volumetric difference between two surfaces. The output is a grid showing the net gain/net loss between two elevation grids.
Denudation rate	Calculates the denudation rate (mm/yr) between two elevation grids subjected to a landform evolution model.

2.6 Conclusions

Since their inception, GISs have evolved and are still evolving from simple graphical tools towards being fully developed 'intelligent' systems. A GIS is currently being used by ***eriss*** as a central management tool to coordinate the storage, manipulation and retrieval of information generated by an investigation into the geomorphological impacts of the ERA Jabiluka Mine, Northern Territory, Australia. Data useful to the project are disparate in terms of location, format and the original context in which it was collected. GISs have the unique ability to store, manage and manipulate these highly variable datasets, providing an environment that eliminates problems such as absence of metadata and multiple copies of the same datasets spread through an organisation.

However, although the range of functionality offered by GIS is continually expanding, standard GIS packages still lack the functionality for complex geomorphological modelling and analysis. An extension to the standard ArcView® GIS software package, 'ArcEvolve', has been developed to provide links between the GIS and SIBERIA landform evolution model. The extension consists of two menus. The first of which allows the user to interact with SIBERIA native format files and parameter database and run the model. The second provides a suite of tools for the geomorphometric analysis of SIBERIA output, allowing a quantitative approach to assessing landform evolution.

3 Rapid erosion assessment

3.1 Introduction

Assessing the long-term impact of mining on catchment geomorphologic processes requires extensive in-depth research, monitoring and collection of data in the field, and sophisticated modelling techniques applied over a period of years. However, before these procedures are implemented it is necessary to quickly acquire and evaluate existing data to assist in the planning of the more detailed monitoring and modelling programs. Erosion hazard models provide a simple and efficient means for assembling available datasets to facilitate a rapid investigation into the physical processes and mechanisms governing soil erosion. Erosion hazard models therefore represent an important step in the risk assessment process. This chapter presents a rapid erosion assessment approach that should form an initial step in a complete erosion risk assessment. The approach is based on a simple erosion hazard model developed through the adaptation of the RUSLE (Renard et al 1994) and is applied here to assess erosion risk within the Ngarradj catchment. Recent data acquisition, including the interpretation of a detailed DEM and collection of sediment discharge data, has allowed the robustness and predictions made by the erosion hazard model to be validated. More precisely, the aims of this chapter are to:

- investigate the effects of elevation data resolution on erosion predictions derived through implementation of a simple erosion hazard model; and
- test the validity of erosion predictions made by the model against sediment discharge data collected from the field.

3.2 Erosion hazard model

The erosion hazard model developed for this project — a simplified form of the RUSLE — does not quantify erosion within a catchment, but rather provides a relative assessment of erosion risk. Rainfall erosivity (R) and the support practice (P) factors have been removed from the original RUSLE equation, such that the erosion hazard model is described by the equation:

$$A = K \times LS \times C \qquad (2)$$

where K is a soil erodibility factor, L is a slope length factor, S is a slope gradient factor and C is a cover-management factor. Rainfall erosivity has been removed from the original equation as, regardless of the actual value of R, this variable remains constant within an area of similar annual rainfall. R can therefore be ignored within an erosion hazard assessment, as it will not be responsible for any variation in erosion prediction within the Ngarradj catchment. The support practice factor, in a natural environment is 1. P can therefore also be removed from the RUSLE (P Puig pers comm 2000).

3.3 Data

A key issue associated with implementing the erosion hazard model is data availability. However, there is commonly a trade-off between data availability and data accuracy/resolution. The 1:50 000 land unit data of Wells (1978) and AUSLIG 1:250 000 elevation and hydrography datasets are widely available and have been shown to be suitable for medium scale erosion assessments. The land units map of Wells (1978) (fig 5) forms part of an increasingly widespread dataset that is being generated as part of a Northern Territory wide mapping program. The mapping program involves extensive field/ground truthing with remotely sensed information. Extra validation of the Wells (1978) land unit data for the Ngarradj catchment primarily consisted of checking the spatial accuracy of the mapped data against a detailed DEM of the catchment. The Wells land unit data were found to be of sufficient accuracy for application of a rapid erosion assessment. The land unit descriptions include information about the soil types, soil surface conditions and vegetation communities within the Ngarradj catchment that can be used to estimate the soil erodibility and cover management factors. A DEM has been interpolated from the AUSLIG elevation and hydrography datasets. Resolution is amongst the most important DEM attributes and will determine the usefulness and cost of a DEM. The DEM was interpolated at a 100 m grid cell resolution. The interpolation algorithm used to create the DEM is based on the ANUDEM program developed by Hutchinson (1989). This interpolation method is specifically designed for the creation of hydrologically correct DEMs from comparatively small, but well selected elevation and stream coverages (Hutchinson 1993). The DEM will provide topographic information for deriving the slope length and slope gradient factors at two different scales.

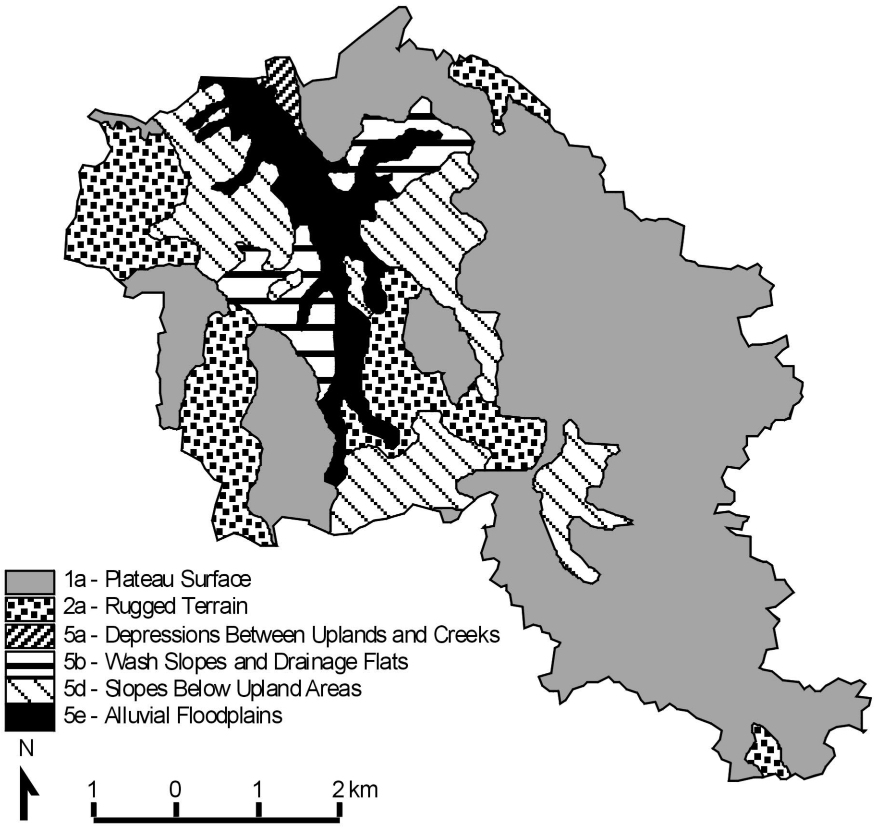

Figure 5 The land units of the Ngarradj catchment

3.4 Derivation of input factors

Implementation and verification of the rapid erosion assessment approach developed within this study was performed within a GIS (ArcView®) on a grid cell basis. The methods employed to prepare the input factors described in equation 3 are described below.

3.4.1 Soil erodibility factor

The dominant soils found within the Ngarradj catchment vary substantially from the shallow lithosol soils associated with areas of sandstone upland plateau to the deep sands of the floodplain alliance (Erskine et al 2001). The land unit descriptions of Wells (1978) provide comprehensive accounts of the soils associated with each land unit. The soil erodibility factor (K) can be derived through analysis of a soil's texture and percentage organic matter. A table produced by Mitchell and Bubenzer (1980) was used to relate the soil texture and organic matter content description for each land unit to soil erodibility values (table 4). The final soil erodibility grids were produced by clipping the soil erodibility coverage using the catchment boundary derived from the DEM of the same resolution, before being converted to a grid.

Table 4 Soil properties of the land units of the Ngarradj catchment

Land unit	Dominant soil	Texture	% Organic matter	K
1a	Shallow lithosols	Sand	<0.5%	0.05
2a	Shallow lithosols	Sand	<0.5%	0.05
5a	Deep earthy sands	Loamy Sand	4%	0.08
5b	Moderately deep siliceous sands	Fine Sand	<0.5%	0.16
5d	Moderately deep siliceous sands	Fine Sand	<0.5%	0.16
5e	Alluvial soils or sands	Sandy Clay	2%	0.13

3.4.2 Slope angle factor

The slope angle factor was calculated from the DEM. The function utilised in the production of the slope grids identifies the maximum rate of change in value from each grid cell to the neighbouring cells using the average maximum technique (Burrough 1986). The slope was calculated as the percent rise, and expressed as a decimal in order to provide comparative values to those provided by the K and C factors. The DEM used in the slope angle calculation covered an area greater than that of the Ngarradj catchment to allow for the flattening effect which occurs when the slope function is applied to cells at the edge of a grid. The slope statistics for the final slope angle factor grid are shown in table 5.

Table 5 Slope statistics for the Ngarradj catchment using a 100 m resolution DEM

Slope (%)	Maximum	Minimum	Mean	Standard deviation
100 m DEM	48.0	0.1	10.6	7.9

3.4.3 Slope length factor

The slope length factor was approximated using two methods. The first, the AF slope length method, attempted to capture the impact of surface runoff on the spatial distribution of erosion risk. This was approximated by calculating a grid that depicts the accumulation of runoff through a digital elevation model. Within the rapid erosion assessment model presented here it is not possible to consider fluvial erosion processes. A threshold was therefore applied to the accumulated flow, with cells having an accumulated flow area of greater than 10 cells considered to be operating under fluvial conditions and masked out of the final analysis. As with the K, S and C factors, the slope length factor grid was normalised to values between 0 and 1.

The second method applied in this rapid erosion assessment, IC slope length, attempted to approximate the length over which water flowed within an individual cell. This method firstly considers the horizontal distance over which the water will move through a cell by examining the direction of the flow, before incorporating the impact of the cell slope on the distance travelled. The function used to incorporate the cell slope is:

$$l = x / \cos \theta \qquad (3)$$

where l is the slope length, x is the horizontal flow distance and θ is the slope angle in degrees. The slope lengths were normalised to values between 0 and 1 to provide values of a similar magnitude to the other factors.

3.4.4 Cover management factor

The cover management factor, which accounts for the protection given by canopy cover, gravel lag and ground cover, is an important factor to be considered when attempting to model soil erosion. The land unit descriptions of Wells (1978) provide qualitative descriptions of both the soil's surface condition and vegetation cover. A cover index (CI), which represents a simple rank from the least protective against erosion (1) to the most protective (5), was then derived for all land units by intuitively comparing the protection against erosion offered either by canopy cover or gravel lag within the different environments. A first approximation of C (C_a) was obtained by calculating the inverse of the cover index (table 6). This relative estimation of the cover management factor was found to be sufficient when providing a rapid, relative assessment of soil loss.

Table 6 The qualitative descriptions of soil and vegetation cover provided by Wells (1978) and the corresponding cover management factor (C_a) value derived for this project

Unit	Soil cover	Vegetation	CI	C_a (1/CI)
1a	Abundant quartz sandstone	Scattered scrub	4	0.25
2a	Frequently stony/gravelly	Grassland to low open woodland	4	0.25
5a	Some coarse quartz sand veneer	Woodland to low open woodland	3	0.33
5b		Woodland with grassland	3	0.33
5d		Variable tall open wood to scrubland	3	0.33
5e		Grassland with areas of woodland	2	0.5

3.5 Results and validation

3.5.1 Elevation data resolution

The erosion hazard model was applied by simply multiplying the input factor grids on a cell-by-cell basis to derive grids of soil loss (A). The resultant soil loss grids were classified into areas of relatively low, moderate and high erosion risk. The thresholds used in the definition of these erosion risk classes were defined by examining the distribution of each dataset. The erosion risk grids were all log-normally distributed. As such, the categories were defined as -1 to 0 standard deviation (low), 0 to +3 standard deviations (moderate) and >+3 standard deviations (high).

DEMs are widely recognised as being highly useful in studies of earth surface processes as they allow the extraction of terrain and drainage features to be fully automated (Wharton 1994). Within this study, the inclusion of a DEM in the rapid erosion assessment approach allowed a more spatially distributed analysis of slope and the calculation of slope length. However, the scale and accuracy of the DEM play an important role in determining its efficacy. The erosion hazard grid produced by applying equation 3 using data derived from the 100 m grid cell resolution is shown in figure 6. The proportion of each land unit occupied by the predicted relative erosion risk classes calculated using the IC slope length and AF slope length methods is shown in table 7.

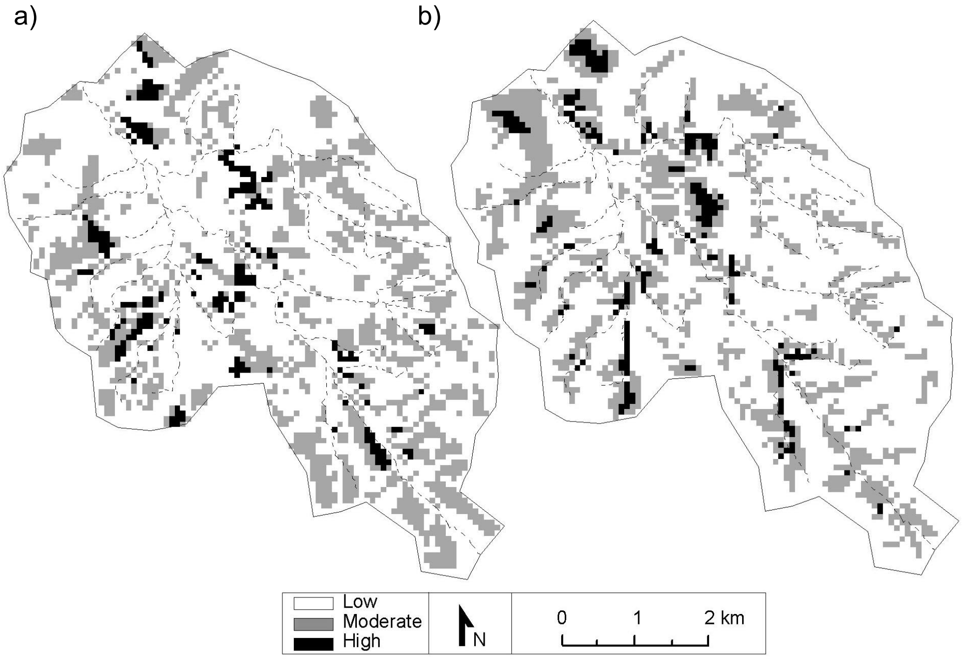

Figure 6 The relative soil erosion risk distribution for the Ngarradj catchment calculated using the 100 m DEM and a) the IC slope length method and b) the AF slope length method

Table 7 Cross-tabulated frequency data (in ha) for the land units grid and 100 m DEM predicted relative erosion risk classes

AF Slope L	1a	2a	5a	5b	5d	5e
Low	214	25	529	344	2429	102
Moderate	111	28	178	322	694	69
High	40	7	4	105	36	32
IC Slope L						
Low	306	23	534	547	2027	159
Moderate	32	13	156	151	1055	31
High	27	24	21	73	77	13

The erosion risk values obtained using both slope length calculation methods appear to correlate well with the land unit descriptions of Wells (1978). That is, the high erosion risk areas tend to be concentrated within the land unit 5d, which contains areas that are highly susceptible to erosion. The upland plateau, primarily composed of highly resistant sandstone, contains the majority of the low erosion potential class. However, the IC slope length method produces results that tend to overestimate the probability of erosion in the upland plateau region and underestimate erosion in the 5d land unit relative to the AF slope length method. When directly compared, the IC slope length method and AF slope length method are shown to produce significantly different results, with the greatest agreement occurring within the low erosion risk class (table 8). Comparison of figure 6a with the slope grid reveals that the rapid erosion model becomes very sensitive to slope when applied using the IC slope length method and high resolution DEM. The AF method, however, provides a more realistic distribution of erosion within the Ngarradj catchment.

Table 8 A contingency table for the IC slope length and AF slope length 100 m erosion grids

		IC Slope L		
		Low (ha)	Moderate (ha)	High (ha)
AF Slope L	Low (ha)	2487	1056	83
	Moderate (ha)	1156	406	18
	High (ha)	34	48	15

3.5.2 Field data validation

The Erosion and Hydrology program at ***eriss*** has established a field project to collect baseline geomorphological data on catchment geomorphology, channel stability, sediment movement and hydrology of the Ngarradj catchment (Erskine et al 2001). These data can be used to assess possible geomorphological impacts arising from the recently established ERA Jabiluka Mine. This mine is adjacent to the World Heritage listed Kakadu National Park and comprises underground mining, contaminant and runoff storage and related surface infrastructure. As part of this project, three gauging stations were established within the catchment (fig 1). Two stations are located upstream of all mine influences, the first on the main right bank tributary of the Ngarradj ('East Tributary') and the second on the main Ngarradj channel ('Upper Main'). The third station ('Swift Creek') is downstream of the mine site. Amongst the data collected at or by these stations are stage height and suspended sediment concentrations. Analysis of these datasets allows the total sediment yield to be calculated for each site.

In order to compare the measured sediment yields with the erosion risk predicted using the rapid erosion assessment method, a series of ratios was established between the three monitored sub-catchments of Ngarradj. Dimensionless ratios between the predicted erosion risk values were calculated through the summation of the predicted risk values associated with each grid cell for each sub-catchment (table 9). In order to calculate ratios between the measured sediment yields for each sub-catchment, a sediment delivery ratio (SDR) had to be approximated, as only a fraction of the sediment eroded within a stream's catchment will be transported to the basin outlet (Walling 1983). This relationship can be quantified by calculating the percentage of the annual gross erosion in a catchment that is measured as the sediment yield at the basin outlet. Approximations of the SDRs for each of the Ngarradj sub-catchments were obtained using the relationship between SDR and drainage basin area developed by the US Soil Conservation Service (Walling 1984) and SDR values obtained for smaller catchments (0.15–0.78 km^2) within the Alligator Rivers Region by Duggan (1988) (table 9). These values were used to convert the measured sediment yield into estimations of gross erosion, thereby enabling comparison of these ratios with the ratios predicted using the rapid erosion assessment method (table 9).

Table 9 Sediment delivery ratios and measured (both unadjusted and SDR adjusted) and predicted soil loss ratios between the sampled sub-catchments

	East Tributary	Upper Main	Swift Creek
SDRs	18%	15%	12%
Measured yield	1	2.32	3.44
Adjusted for SDR	1	2.79	5.17
AF Slope L	1	2.56	6.22
IC Slope L	1	3.30	7.30
Catchment area	1	2.25	5.12

The ratio of sediment loss between the East Tributary, Upper Main and Swift Creek sub-catchments is shown in table 9 for both field measured and predicted values. Sediment yields, adjusted using approximations of each sub-catchment's SDR, indicate that there is a non-linear relationship between catchment area and sediment loss within the Ngarradj catchment. This non-linear relationship is also shown by applying the erosion hazard model to the 25 m Ngarradj DEM (fig 7). However, the slope of this line is much greater than that relating area to the adjusted sediment yield, with a significant under-prediction of erosion in the East Tributary sub-catchment relative to the Upper Main and Swift Creek sub-catchments. The most accurate prediction of the relationship between erosion in the Upper Main and East Tributary sub-catchments, relative to the measured soil loss, was made using the 100 m interpolated DEM and AF slope length method (table 9). However, the relative sediment loss is over predicted using this dataset for the Swift Creek – Upper Main relationship as the relationship continues a linear trend and does not flatten out between these two points. These results indicate that the rapid erosion assessment method tends to be increasingly influenced by area with decreasing data resolution, with a general under prediction of net erosion over smaller areas and over prediction in larger areas.

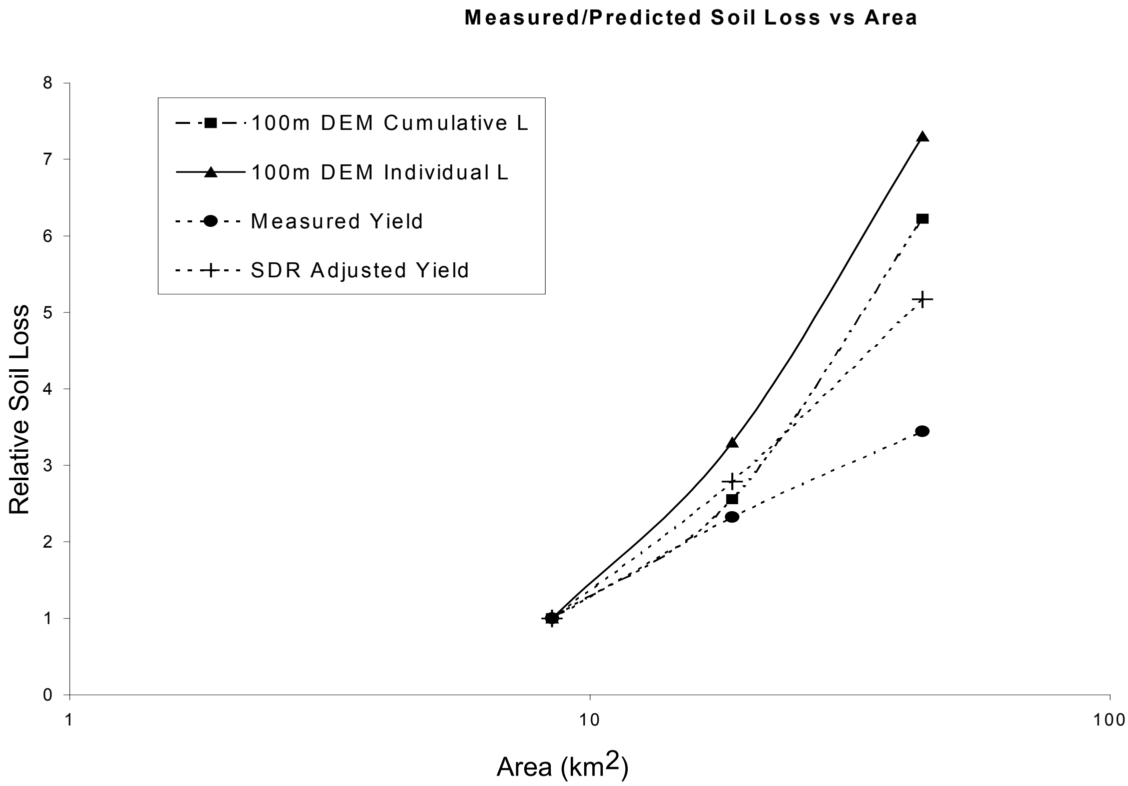

Figure 7 The relationship between relative soil loss and area for both the measured and predicted values

4 Initial landform evolution modelling and basin analysis as a basis for risk assessment

4.1 Introduction

The SIBERIA landform evolution model is a sophisticated three-dimensional topographic evolution model. The model has been used to investigate post-mining rehabilitated landform design at the ERA Ranger Mine since 1993 (Willgoose & Riley 1993, Evans 1997, Evans et al 1998, Willgoose & Riley 1998, Evans 2000). To date, the model has principally been used to examine landform evolution on post-mining rehabilitated landforms or small natural catchments. This study applies the model to a medium-scale catchment and assesses the potential for applying the model to a medium-scale, mining affected catchment for risk assessment.

SIBERIA is a complex landform evolution model that requires extensive parameterisation (Willgoose et al 1991). Parameterisation of the model requires the use of separate hydrology and sediment transport models to derive a discharge/area relationship, long-term sediment loss and a sediment transport rate (fig 8) and has been discussed extensively by Evans et al (1998) and Willgoose and Riley (1998). The initial parameterisation and application of the model has been presented in Boggs et al (2000). The application of the initial parameters to the modelling of landform evolution in the Ngarradj catchment identified significant inaccuracies in the modelled results. This has been attributed to the complexity of the Ngarradj catchment and to the use of only one year of observed data. This chapter presents a revision of these initial parameter estimations and a new method for calibrating the sediment transport rate parameter, β_1, to complex catchments. A simple sensitivity analysis of the impact of the discharge area relationship on the derivation of the β_1 parameter is also discussed. The fitted β_1 and derived parameters are used in an assessment of future landform evolution in the Ngarradj catchment.

The initial SIBERIA simulations allow a qualitative risk assessment of Ngarradj catchment change at this stage of the study. It is proposed that the qualitative risk assessement can be complemented by a quantitative risk assessment of SIBERIA output through basin analysis. The basis analysis is conducted using the geomorphometric measures described in section 1.3.3 through comparison of 0 year basin form and the 1000 year basin form. An assessment of the applicability of the techniques is presented here.

4.2 Landform evolution modelling

SIBERIA model structure and parameterisation has been discussed previously (Evans et al 1998, Willgoose & Riley 1998, Boggs et al 2000, Moliere 2000). SIBERIA predicts the long-term average change in elevation of a point by predicting the volume of sediment lost from and added to a node on a DEM using the fluvial sediment transport equation:

$$q_s = \beta_1 q^{m_1} S^{n_1} \qquad (4)$$

where: q_S = sediment transport rate (m^3 y^{-1}), S = slope (m/m), β_1 = sediment transport rate coefficient; and m_1 and n_1 are fitted parameters. Q = discharge or peak discharge and is dependent on drainage area as follows (Leopold et al 1964):

$$Q = \beta_3 A^{m_3} \qquad (5)$$

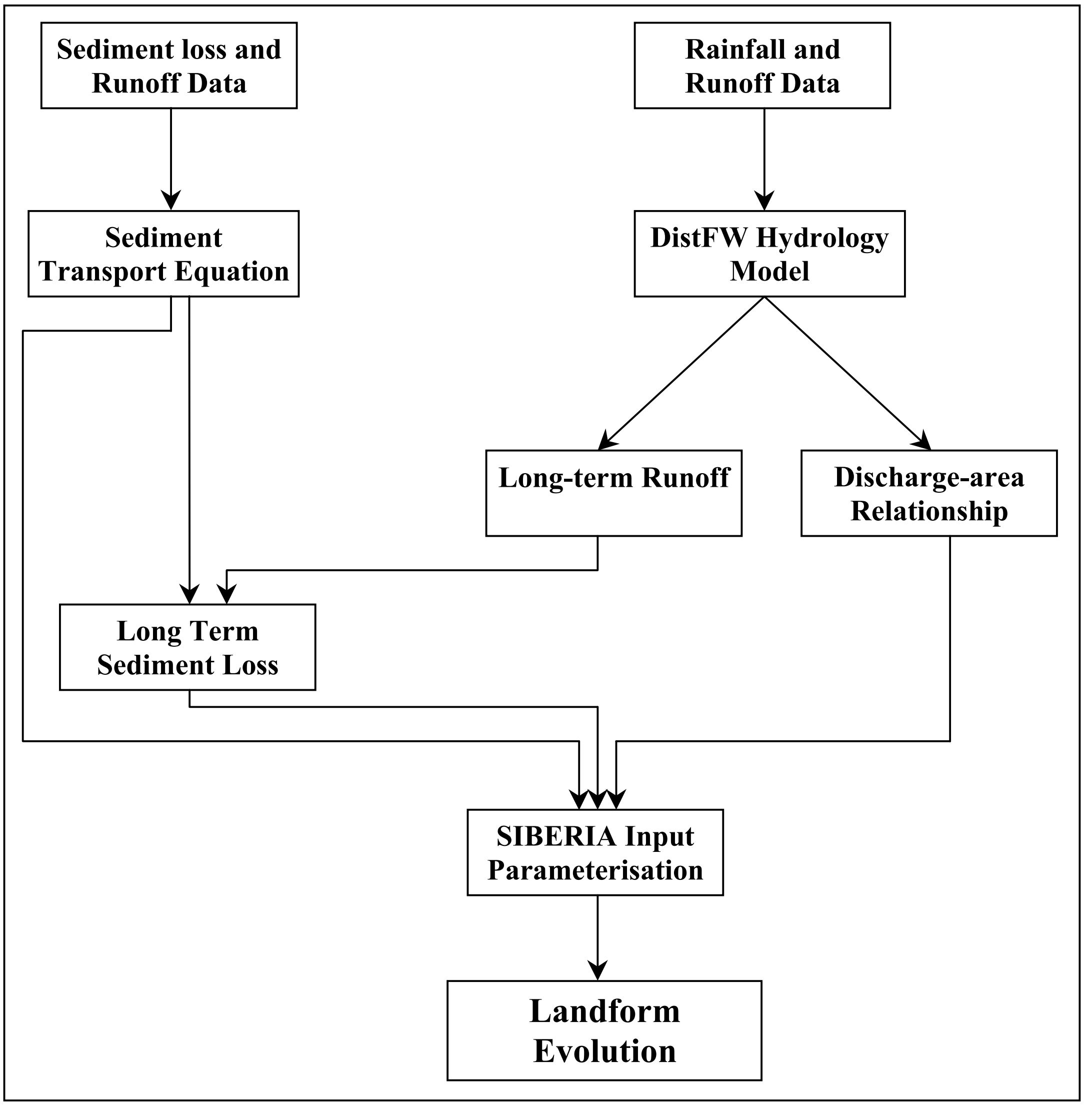

Figure 8 A flow diagram depicting the processes involved in the parameterisation of the SIBERIA landform evolution model (after Evans et al 1998)

To run the SIBERIA model for a field site it is necessary to derive parameter values for β_1, β_3, m_1, n_1 and m_3.

Parameter values for equations (4) and (5) are derived by:

- calibrating a hydrology model using rainfall-runoff data from field sites (section 4.2.1);
- fitting parameters to a sediment transport equation using data collected from field sites (section 4.2.2); and
- deriving long-term average SIBERIA model parameter values for the landform being modelled (section 4.2.3).

Once parameters have been fitted to the sediment transport equation and the DistFW rainfall-runoff model for a site, the results are used to derive SIBERIA input parameter values for the landform to be modelled.

The SIBERIA input parameter derivation process (steps 1 to 3 above) and models used are described in detail by Willgoose and Riley (1993) and Evans et al (1998). The following sections give results of parameter derivation for the Ngarradj catchment for this study.

4.2.1 DistFW hydrology model

The DistFW hydrology model (section 2.5.1) parameter values fitted in this preliminary study using non-linear regression (Willgoose et al 1995) were:

- sorptivity (initial infiltration) — Sphi (mm $h^{-0.5}$);
- long-term infiltration — phi (mm h^{-1}); and
- kinematic wave coefficient and exponent, — c_r ($m^{(3-2e_m)}s^{-1}$) and e_m

Calibration of the DistFW hydrology model involves fitting parameters values to selected catchment storm event data. The average rainfall, calculated from the data collected at each stream gauging station (fig 1), was plotted with discharge for the Ngarradj downstream gauging station for the 1998/1999 Wet season. Two large and two moderate discharge events were selected to be input for calibration of the hydrology model.

Parameter values were fitted to the selected hydrographs for the observed rainfalls by fitting a single parameter set that provided a good fit to the four hydrographs for each site simultaneously. The predicted event hydrographs compared reasonably well with observed data for each event (fig 9). There was some over-prediction of the peak discharge of one of the events. However, the over-prediction of runoff is preferred to under-prediction, as this results in higher predicted sediment movement which in turn provides a basis for more conservative management of mining impact. The final parameters were assessed by comparing the predicted total discharge and hydrograph for the entire 1998/1999 Wet season with the observed total discharge and hydrograph. The predicted total discharge for the Ngarradj catchment at the downstream gauging station was found to be slightly less than the observed value (table 10), whilst the hydrographs were similar in shape.

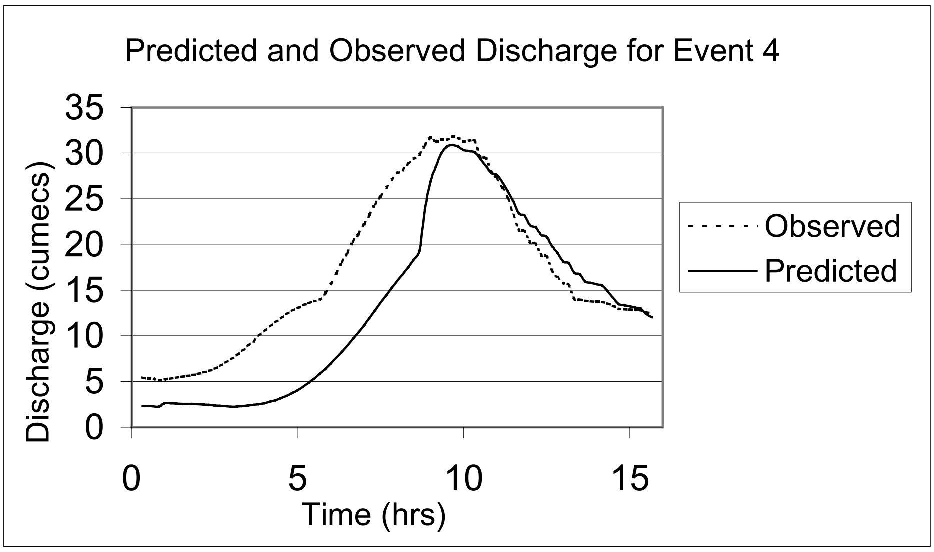

Figure 9 An example of a predicted hydrograph produced by DistFW compared with the observed hydrograph

Table 10 The observed and predicted discharges for the 1998/1999 Wet season in the Ngarradj catchment

Observed discharge (ML)	Predicted discharge (ML)	Difference (%)
33 660	31 576	6.5

4.2.2 Sediment transport model

The initial parameterisation of the sediment transport model in Boggs et al (2000) used only one year of data. This relationship has been re-examined following processing of the 1999/2000 hydrology and suspended sediment data. The sediment transport model (equation 1) was fitted using iterative multiple regression on a log transformation (Evans 1997, Moliere et al 2001). The updated model is

$$T = 0.00136 \int Q^{1.38} dt \; * \; \eta \; (r^2 = 0.98; \text{no. of obs} = 14; p < 0.001, \eta \approx N(1, \sigma)) \qquad (6)$$

However, it is important to note that at this stage of the study the sediment transport model only considers suspended sediment transport and does not account for sediment transported as bedload or solutes.

4.2.3 Average SIBERIA input parameter values

4.2.3.1 Discharge area relationship

Equation 5 has long been used as the form for equations that relate discharge to area. However, the discharge term, *Q*, has been defined differently by many people. Willgoose et al (1989), for example, propose that the appropriate discharge to use in determining the long-term elevation change due to fluvial transport is the mean peak discharge. Hack (1957), on the other hand, parameterises the discharge area relationship using average instantaneous discharge, whilst Leopold and Miller (1956) define *Q* as the peak discharge equalled or exceeded in 2.3 years. Furthermore, in previous SIBERIA studies (Evans et al 1998, Willgoose & Riley 1998, Moliere 2000), the discharge area relationship (equation 5) has been determined through scale analysis due to the lack of total catchment discharge data. Because of the availability of total catchment discharge data in this study, the area dependence of discharge within the Ngarradj catchment has been derived using observed discharge data from the field monitoring program (fig 10).

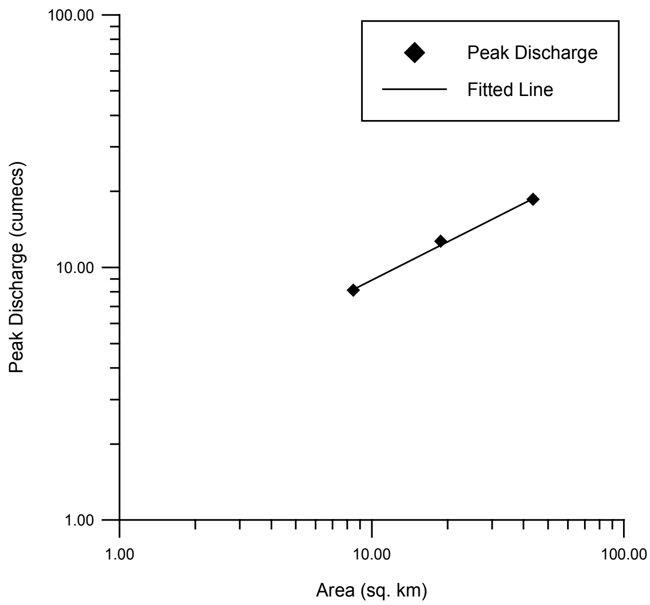

Figure 10 The peak discharge/area relationship exhibited by the field data

A flood frequency analysis, in which the magnitude of a flood of a particular probability of exceedence, has been conducted for the Ngarradj catchment (Moliere et al 2001). The analysis was conducted using a partial series approach as there are only two years of continuous streamflow data. The eight events used to determine the flood frequency distribution were selected as events greater than a predefined base discharge and were separated by a minimum of 7 days. Table 11 provides a summary of the peak discharges for various year return periods at SC, UM and ET and the respective β_3 and m_3 parameter values. The acceptable range for m_3 values is approximately 0.5 to 1.0 (Willgoose et al 1991). The value of the m_3 parameter has been found to approximate 1.0 using mean annual discharges and to approach 0.5 during higher flows (Flint 1974, Leopold et al 1964, Rodriguez-Iturbe & Rinaldo 1997). The values determined here approach the higher end of the flow spectrum.

Table 11 Summary of flood frequency distribution for each gauging station

Site	Discharge ($m^3 s^{-1}$)					
	$Q_{1.01}$	$Q_{1.11}$	Q_2	$Q_{2.33}$	Q_5	Q_{10}
SC	14.3	15.7	18.2	18.6	20.3	21.7
UM	10.3	11.0	12.4	12.7	13.8	14.7
ET	6.47	7.27	8.05	8.12	8.41	8.56
β_3	0.003	0.0042	0.0029	0.0026	0.0016	0.0011
m_3	0.4827	0.469	0.497	0.5049	0.5366	0.5663

The discharge area relationship reported for the Ngarradj catchment in Boggs et al (2000) was calculated using observed peak discharges from one season of measured data. The availability of a flood frequency distribution means that the discharge area relationship should be revised. The discharge selected as being the most appropriate for this study was the 2.33 year flood event discharge. The selection of a particular flood event to calibrate the discharge area relationship was found to not impact significantly on the β_1 parameter (equation 4), as the sensitivity of β_1 to β_3 and m_3 was assessed and found to be negligible. However, a thorough analysis of the sensitivity of the SIBERIA model to the β_3 and m_3 parameters should be conducted in future studies (see section 5.3).

The discharge area relationship fitted for this study is therefore:

$$Q = 0.0026\, A^{0.5049} \tag{7}$$

where Q is in cumecs and A is in m^2.

4.2.3.2 Runoff series and long-term sediment loss rate

The runoff series for the Jabiru historical rainfall record was used to determine the long-term erosion rate (q_3) in equation 4 for the Ngarradj catchment.

The steps were:

- The fitted DistFW model parameter values were used to generate long-term runoff for the Ngarradj catchment for several years of the Jabiru rainfall record. The sub-catchment model of the stand-alone version of the DistFW model was used because of the large amount of computer processing time required to generate a runoff series using DEM node data.
- The annual runoff was then used in the soil loss equation (equation 6). The annual sediment loss ($Mg\ y^{-1}$) calculated using this equation was converted to a volume ($m^3\ y^{-1}$) by dividing by the bulk density of the surface material ($1.38\ Mg\ m^{-3}$) (table 12). Using

the annual sediment losses a long-term average sediment loss rate was then determined (q_3) for equation 4 (table 12).

The value of q_s was then used to determine β_1 by substituting equation 5 into equation 4 and transposing to give:

$$\beta_1 = \frac{q_s}{\beta_3^{m_1} A^{m_1 m_3} S^{n_1}} \tag{8}$$

where A is in m^2. The slope, S, represents the hydraulic slope at the point for which the sediment discharge (q_s) has been calculated. A slope of 0.0013 m/m was approximated using elevation values obtained from the Ngarradj DEM on a relatively constant slope channel section. The value of n_1 was fixed at 0.69, as this value been used in previous studies within the region (Evans et al 1998, Willgoose & Riley 1998). Equation 8 was thus solved to provide a β_1 of 1765.6. This compares with a value of 628.7 solved in Boggs et al (2000) using the one year, monitored peak discharge area relationship.

Table 12 Calculation of the long-term average soil loss for the Ngarradj catchment

Year	Rainfall (mm)	Discharge (ML)	Soil loss mass rate (Mg y^{-1})	Soil loss volume rate (m^3 y^{-1})
1972	1163	26965	1020	739
1973	1353	31451	1343	973
1974	1604	38985	1482	1074
1975	1642	42278	1929	1398
1977	928	25126	1017	737
1978	1467	39786	1666	1207
1979	1193	32198	1192	864
1980	1663	44467	1918	1390
1984	2082	54210	2569	1862
1986	1145	28668	917	665
1987	1277	32244	1352	979
1988	1135	29151	1051	761
1989	1152	26516	942	683
Average values	1370	34773	1415	1026

4.2.3.3 Slope correction

The q_S value (equation 4) is implicitly derived using a real value for slope (S = 0.0013 m/m). However, SIBERIA operates on a node by node basis where each node in the DEM is assumed to have a dimension of 1. Therefore β_1 (equation 4) needs to be adjusted to account for the error in calculating slope over a length of 1 ie each node is considered to be 1 unit area, and S reflects the number of metres drop between nodes, which are 50 m apart for the Ngarradj catchment DEM. S values required for the soil loss equation, on the other hand, are in m/m. To correct this in SIBERIA, β_1 must be reduced to reflect the slope calculated by SIBERIA and the correction factor is as follows:

$$\frac{1}{(DTM\ spacing)^{n_1}} = \frac{1}{50^{n_1}} \tag{9}$$

The value of the β_1 parameter used in SIBERIA must include a multiplication by the correction factor derived in equation (9). Applying the correction factor to equation (9), a value of 118.7 was solved for β_1. The internal algorithm in SIBERIA corrects for true DEM node slope during simulations.

Denudation rate β_1 adjustment

The measurement of a long term average soil loss volume rate in section 4.2.3.2 allowed the determination of a long-term denudation rate, based only on suspended sediment losses, for the Ngarradj catchment of 24 mm ky^{-1}. This denudation rate is appropriate for this study as only suspended sediment data was used in the fitting of the sediment transport equation and β_1. The long-term denudation rate calculated using the modelled catchment after a 1000 year simulation within SIBERIA with a β_1 value of 118.7 was higher than the measured rate (36 mm ky^{-1}). This error requires further investigation, but is currently believed to relate to the complex nature of the Ngarradj catchment and the simple, single parameter approach used in this initial modelling of the long-term landform evolution of the Ngarradj catchment. An iterative regression approach was therefore established to fit a β_1 that produced a denudation rate equivalent to the measured denudation rate. A new β_1 value of 85, adjusted for slope, was produced using this approach. This value was used in the final modelling of the long-term evolution of the Ngarradj catchment.

4.2.4 Initial model application

The evolution of the Ngarradj catchment was modelled for a period of 1000 years using the parameters derived in the previous sections. Figure 11 shows the areas of erosion and deposition predicted by SIBERIA. No quantitative scale has been placed on the grey scale in figure 11 at this stage because of the difficulty in assigning spatial changes in model parameters to the competent, erosion resistant sandstone escarpment and uplands. That is one set of parameter values has be used for the whole catchment with no spatial variation for different land units.

Figure 11 shows a clear differentiation in geomorphological activity between the less active floodplain areas and the more active upland plateau of the Ngarradj catchment. The upland plateau region can be seen to have widespread erosion of the surface. The highest incision occurs within small tributary valleys located on the sandstone uplands. Areas of high deposition predominantly occur where these tributaries debouche either directly onto the Ngarradj floodplain or the upper Ngarradj valley. However, using one parameter value set applied to the whole DEM surface results in over-prediction of erosion and subsequent deposition over the upland plateau surface. This indicates that the upland plateau region and floodplain region should be modelled as separate entities, with a specific set of parameters derived for each zone. The application of spatial variation in parameter values to account for the low erodibility sandstone escarpment and plateau surface will be addressed in future research. Therefore interpretation of erosion and deposition at these areas can only be qualitative at this stage of research. The floodplain region of the Ngarradj catchment, on the other hand, shows widespread but low levels of deposition around the main creek channels and limited erosion on the interfluve areas. However, an extensive backwater floodplain exists between the confluence of the Magela Creek and Ngarradj and the most downstream location covered by the Ngarradj DEM. It is expected that a large proportion of the sediment moving from the Ngarradj catchment is deposited in this region. Future acquisition of digital elevation data for the backwater floodplain will allow investigation of these processes.

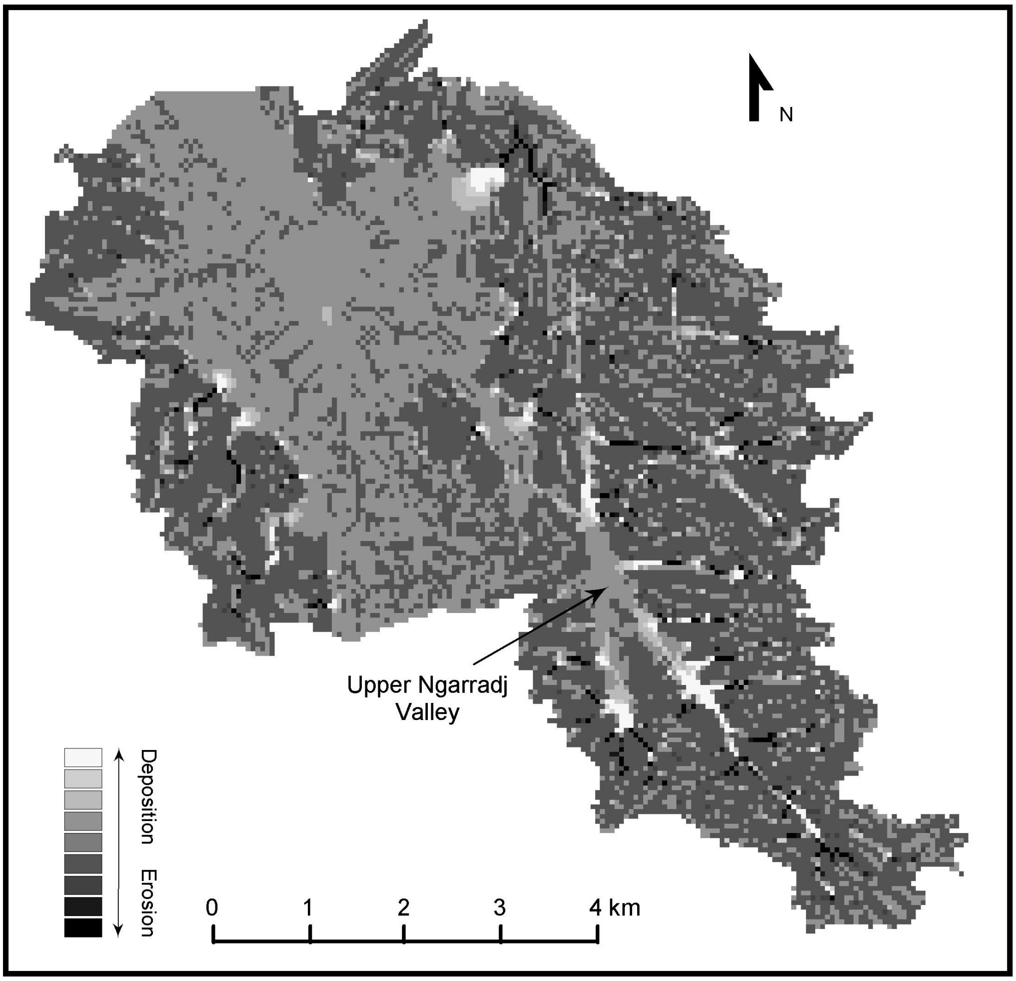

Figure 11 Differences in elevation, indicating areas of erosion and deposition, between the Ngarradj catchment at 0 years and after being modelled for a period of 1000 years

4.3 Basin analysis

To assess risk, the qualitative landform evolution modelling needs to be complemented with quantitative techniques. The geomorphometric measures discussed by Hancock (1997) have potential to quantify catchment change and therefore assess the risk of impact by catchment disturbance.

This section applies the geomorphometric measures using the GIS tools discussed in section 1.3.3 to the Ngarradj catchment to compare the quantitative geomorphology of the catchment at 0 years and after 1000 years of simulated evolution using SIBERIA.

4.3.1 Hypsometric curve

The hypsometric curve, describing the distribution of area with elevation, provides a quantitative means for characterising the planimetric and topographic structure of a catchment (Luo 1998). The hypsometric integral, the area under the curve itself, also provides a measure of dissection of a landscape. Small hypsometric integrals indicate that the catchment is composed of a plain with small hummocks, whilst a high value represents a plain with narrow incision. Analysis of the hypsometric curves for the 1000 year simulated Ngarradj catchment and year 0

Ngarradj catchment (fig 12) reveals little difference between the curves and hypsometric integrals. This is to be expected in a relatively stable, natural catchment where there would be little change over 1000 years as indicated by the studies of Moliere (2000). However, the change that has occurred, including a lowering of the hypsometric integral, indicates that SIBERIA is correctly simulating the evolution of the catchment towards a more mature state.

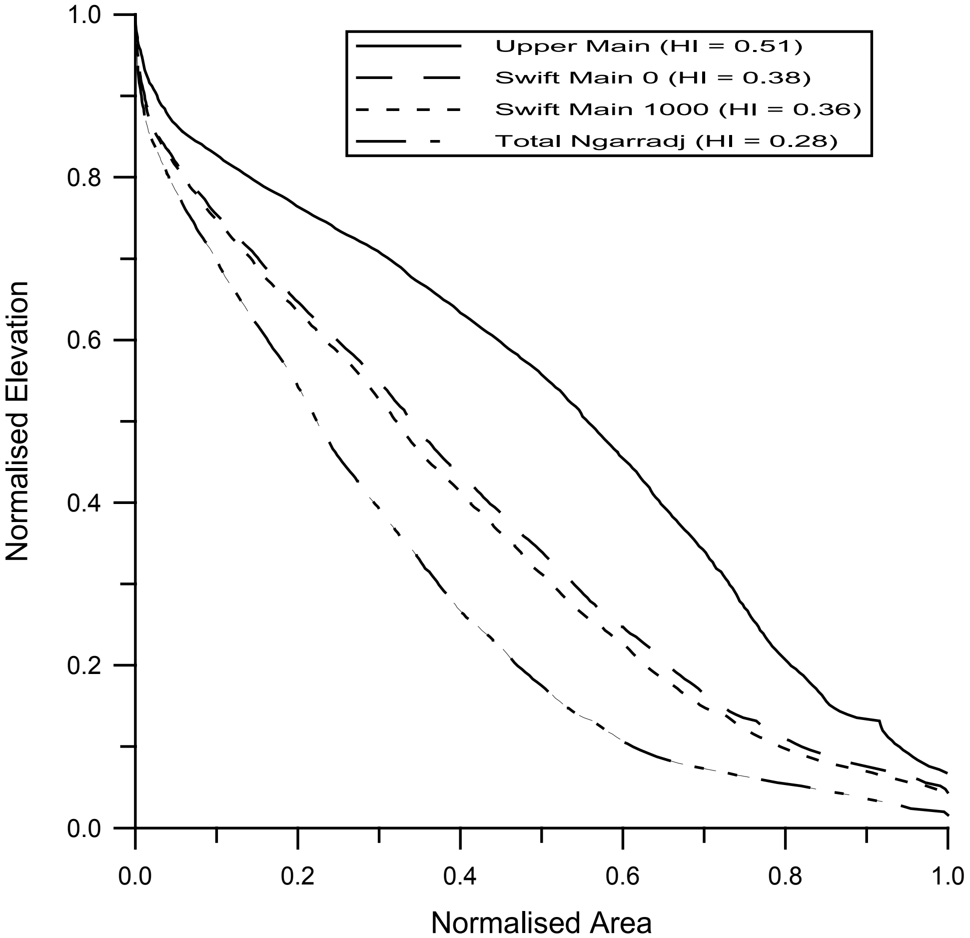

Figure 12 The hypsometric curves and integrals (HI) for the Upper Main, Swift Creek (0 and simulated 1000 year catchments) and total Ngarradj catchments

The relationship between catchment maturity and hypsometric curve can be seen in the Ngarradj catchment by examining the hypsometric curves and integrals of the Upper Main catchment, Swift Creek catchment and total Ngarradj catchment. These catchments, representing increasingly larger portions of the Ngarradj catchment, have hypsometric integrals that decrease with increasing area (fig 12). The trend in the hypsometric curves and integrals reflects the evolution of a drainage basin due to fluvial processes (Strahler 1957). That is, the Upper Main catchment represents a 'youthful' stage in the evolution of the Ngarradj catchment where slope changes take place relatively rapidly as the drainage networks expand. The Swift Creek catchment represents a more mature stage in which a stable hypsometric curve has developed as the relief diminishes. Finally, the total Ngarradj catchment is more akin to the 'monadnock stage' in which the catchment is dominated by a subdued plain area with isolated bodies of resistant rock (Hancock 1997).

4.3.2 Width function

The simplified and original width functions (section 1.3.3.3) have been applied to the 1000 year and 0 year simulated Ngarradj catchment (figs 13 & 14). The width functions have been calculated using a standard 600 m interval distance from the outlet as this was found to provide the clearest description of catchment structure. The simplified width function has been found to primarily describe the shape of a catchment. The simplified width functions for the 1000 year and 0 year simulated Ngarradj catchments are very similar, with only a slight difference at the first major peak. This is to be expected in a relatively stable, mature natural catchment. The relatively rapid peak and subsequent tapering off of the curves reflects the substantial width of the catchment near the catchment outlet and the gradual narrowing of the catchment with distance from the outlet.

The original width function provides a more accurate description of the spatial pattern of the water courses within a catchment (Naden 1992). However, the application of this function requires the prior definition of a stream network. Stream networks are often derived from DEMs by thresholding the drainage area required to generate a stream (Jenson & Domingue 1988). A relatively arbitrary area of 10 ha was defined as the minimum upstream contributing area required to generate a stream for the calculation of the original width function (fig 15). The 0 year and 1000 year simulated Ngarradj catchments have very similar original width functions. These functions, like the simplified width function, have relatively rapid peaks and taper off with increasing distance from the outlet. However, there are some noticeable differences between the 0 year and 1000 year original width functions for >10 ha drainage areas. The original width functions indicate a general increase in the drainage density through time, with the total number of drainage lines intersected by the 1000 year function being 3% greater than the number intersected in the 0 year function. The 0 year function has a sharp initial peak (at approx 3 km) and broad second peak (at approx 5 km), whilst the 1000 year function has a broader first peak and sharp second peak. This indicates that there has been a slight increase in the length of drainage density around 3 km from the drainage outlet and a decrease in the length of drainage density at 5 km.

4.3.3 Cumulative area diagram

The cumulative area diagram describes the spatial distribution of areas within a catchment (Hancock 1997). The cumulative area distribution calculated for the 0 year and 1000 years simulated Ngarradj catchments are shown in figure 15. As with most catchments, the cumulative area distributions for the Ngarradj catchments can be divided into three regions. The first region, defined by the first break in slope of the cumulative area distribution (at an area of approx 15 pixels), represents those small areas of the catchment where rainsplash or interrill erosion is the dominant erosive mechanism. The two catchments exhibit identical behaviour in this region of the diagram, indicating that there is little change over a period of 1000 years in the areas of hillslope flow aggregation. The second region occurs between an area of approximately 15 pixels and 5000 pixels. This region, representing the area dominated by channelised flow, exhibits an increase in area over the 1000 year modelled period. This indicates that there has been an increase in the number of channels draining the hillslopes. The most observable difference, due to the logarithmic scales, occurs in the third region of the cumulative area diagram, with a relatively significantly smaller proportion of the catchment area occurring in this region at 1000 years than at 0 years. This region consists of that part of the catchment dominated by large channels with large contribution areas. The distribution therefore decreases rapidly as a result of increasing drainage area (Hancock 1997).

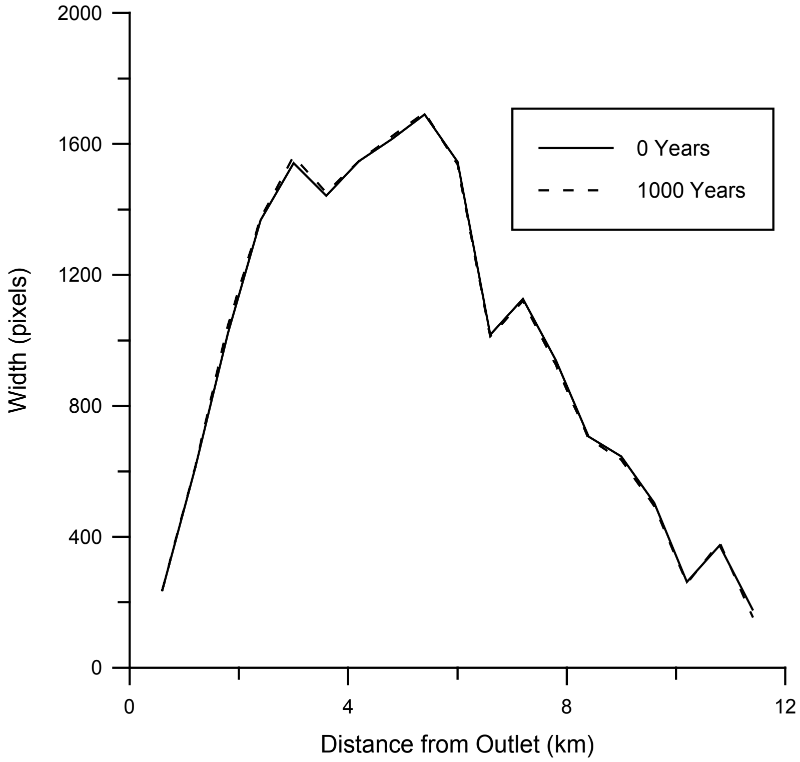

Figure 13 Simplified width functions for the Ngarradj catchments using the 0 year and simulated 1000 year catchments

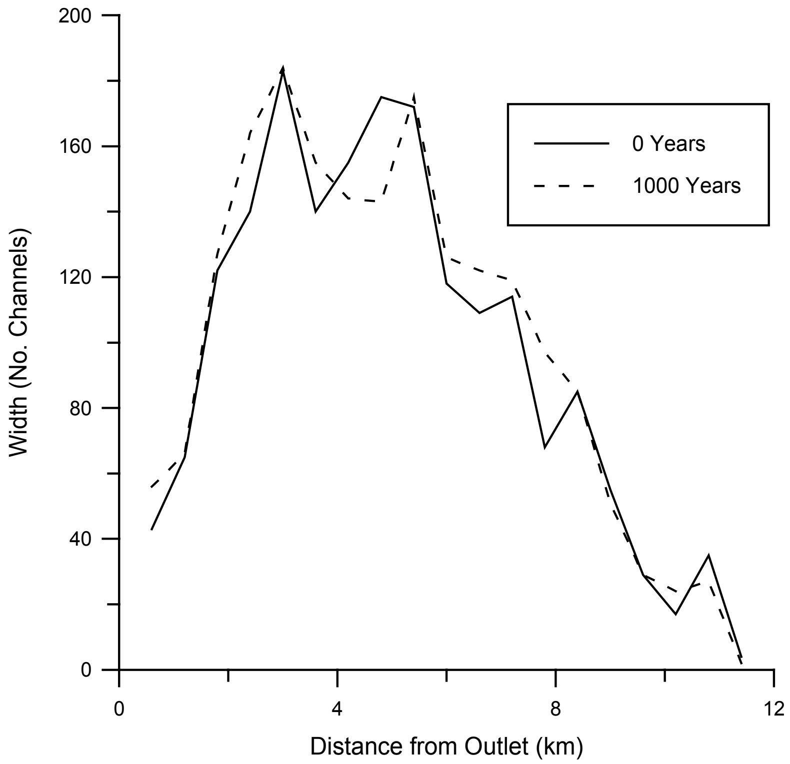

Figure 14 Original width functions for the Ngarradj catchments using the 0 year and simulated 1000 year catchments where stream channels are defined as areas with drainage areas greater than 10 ha

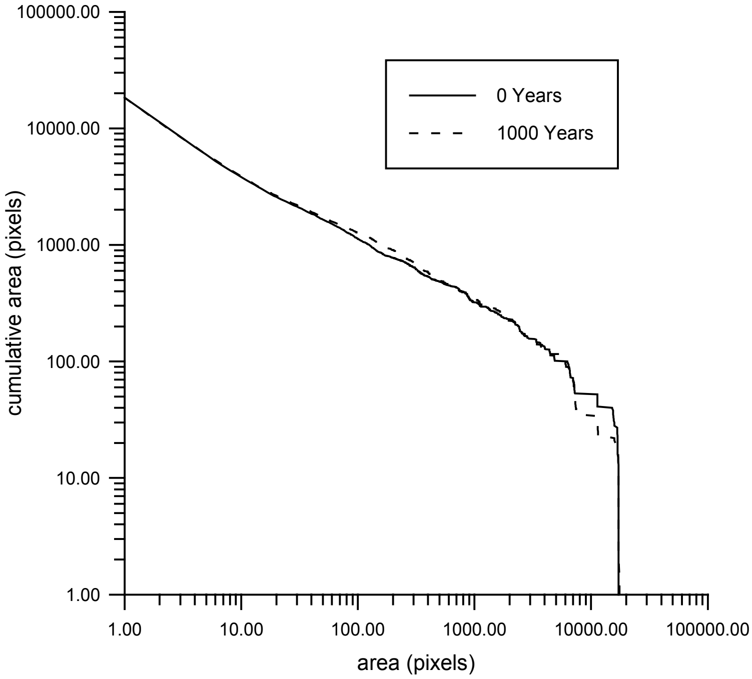

Figure 15 The cumulative area diagrams for the 0 year and 1000 years simulated Ngarradj catchments

4.3.4 Area-slope relationship

The area-slope relationship, calculated as the number of pixels draining through a point (area) versus the slope at a point, has been used to compare different catchments (Hancock 1997). However, the area-slope relationship for the Ngarradj catchment does not follow a simple trend and therefore is not appropriate for examining the evolution of the Ngarradj catchment over 1000 years in this study (fig 16). This is a product of the complexity of the catchment as it contains two significantly different geomorphological regions. The upland plateau region, composed of highly dissected sandstone, is dominated by extremely flat plateau surfaces and vertical cliff faces and therefore does not follow the typical area-slope distribution. Furthermore, the juxtaposition of steep slopes and flat areas in the plateau region may mean that slope is not appropriately represented at a 50 m pixel scale. The lowland region, on the other hand, is relatively flat with a maximum slope of approximately 15%.

4.4 Application to risk assessment

Initial landform evolution simulations indicate that SIBERIA can be calibrated to the Ngarradj catchment. There was difficulty in fitting β_1 and the reason for this needs to be further investigated. Notwithstanding the 1000 simulated landform gives a good qualitative assessment of what erosion and deposition will occur in the catchment.

All the geomorphometric measures, except for the area-slope relationship, could be applied to this very complex catchment for basin analysis. These measures allow a more quantitative assessment of catchment change than interpretation of the simulated 1000 year DEM alone. The geomorphometric measures indicate that little change occurs in the undisturbed catchment over 1000 years. This result is similar to that of Moliere (2000) who found that there is little change in both channel and sheetflow SIBERIA input parameter values for mature landforms in the Alligator Rivers Region. The similarity in results between the two studies tends to validate the geomorphometric measures technique.

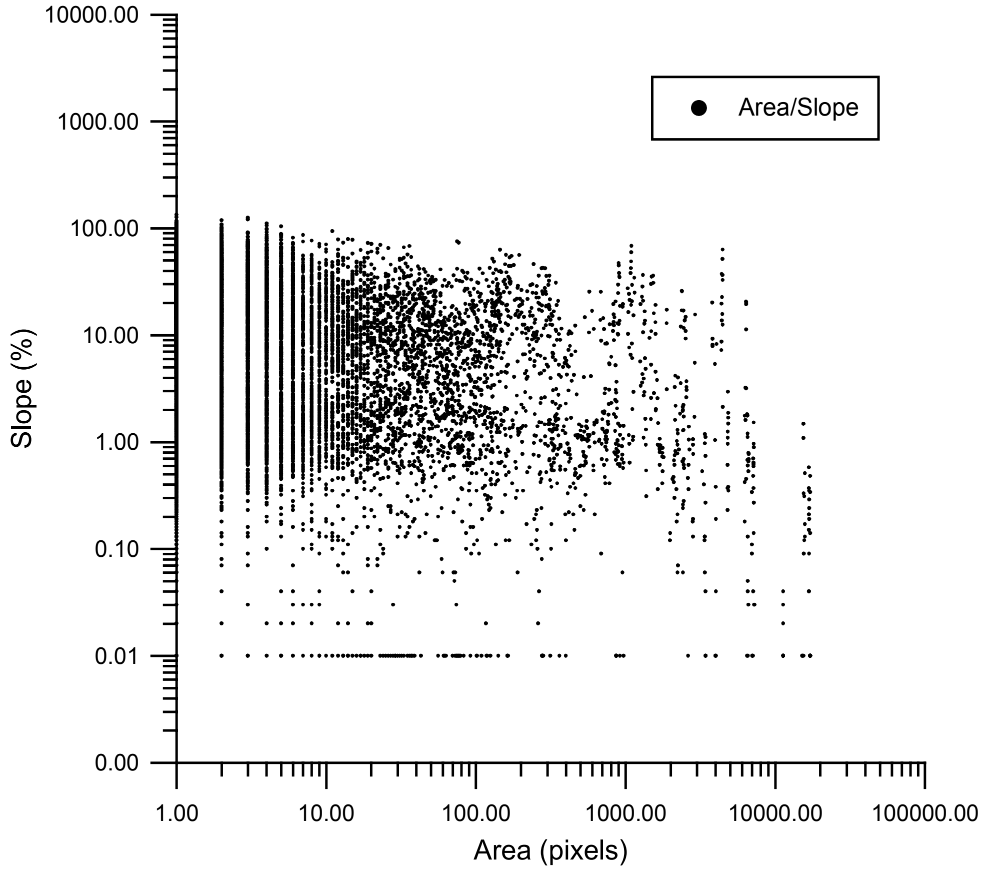

Figure 16 The area-slope relationship for the Ngarradj catchment

To undertake a risk assessment the following should be completed:

1 The landform evolution modelling and basin analysis should be applied to the undisturbed catchment;

2 A DEM for the conceptual rehabilitation design for the Jabiluka mine should be developed and superimposed on the undisturbed catchment;

3 SIBERIA input parameters should be spatially distributed to reflect disturbed and undisturbed areas of the catchment; and

4 Conduct both landform evolution simulation and basin analysis of the disturbed catchment and compare with the results of dot point 1 above to assess both spatial and temporal impact.

Future work in this project will collect the data required to derive input parameter values for the mine site rehabilitation design and address parameter value derivation refinement so that the risk assessment can be completed.

Conceptually these techniques have broad application and can be applied to risk assessment of catchment disturbances other than those caused by mining. The technique allows both spatial and temporal risk assessment.

5 Future research

5.1 Introduction

This report discusses major progress in the research area of GIS application to the assessment and management of mining impact. Three areas have been identified as requiring further study in order to provide a more valuable approach to assessing mining impact: (i) the incorporation of spatial variation in SIBERIA input parameter values in the modelling process; (ii) an analysis of the sensitivity of the SIBERIA model to input parameter value variations or error; and (iii) the practical application of the developed technology to assessing the impact of the ERA Jabiluka Mine on landform evolution in the Ngarradj catchment.

5.2 Incorporation of spatial variation in parameters

5.2.1 Parameter value derivation

The landform evolution model, SIBERIA, has been used to investigate erosion and hydrological processes operating on post-mining landforms (Evans et al 1998, Willgoose & Riley 1998, Hancock et al 2000b) and small natural catchments (<55 ha) (Hancock et al 2000a). However, the majority of these studies have been conducted using constant parameter values reflecting the initial conditions of one area of the landform or catchment with no consideration of the spatial variation in surface conditions, such as vegetation cover, soil erodibility or management practices. A recent study by Ferguson (1999) is the first attempt to incorporate the spatial variation in parameter values into the SIBERIA landform evolution modelling process. The study by Ferguson investigated the effect of spatial variation in surface treatment parameters on SIBERIA simulations of the proposed ERA Ranger Mine above-grade rehabilitated landform. Through comparison of a spatially varied simulated landform with landforms derived through three single parameter simulations, it was found that the inclusion of spatial variability significantly altered the evolution of the landform. Further studies were found to be required to establish whether these differences were natural or consequences of the modelling process, caused by inaccuracies in the modelling of spatial variation or the use of an excessively coarse grid cell resolution.

This project, representing the first attempt to apply SIBERIA to the assessment of mining impact on a medium-sized catchment, will require the inclusion of the spatial variation in parameter values to accurately model landform evolution. The total Ngarradj catchment, covering an area of almost 67 square kilometres, includes 3 major geomorphic regions including the Ngarradj backwater floodplain adjacent to the Magela floodplain, the Ngarradj lowlands with deep sandy soils and an upland plateau region with highly dissected sandstone and shallow sandy soils. When modelling long-term landform evolution in a catchment of this size, it is necessary to consider the natural heterogeneity in landform surfaces. The derivation and spatial mapping of these natural catchment parameters will occur through analysis of the gauging station data as well as DEM and remotely sensed imagery classifications.

Research by Ferguson (1999) at the ERA Ranger Mine has also demonstrated the impact of including mine site heterogeneity in the modelling process. The assessment of landform evolution at Jabiluka and the wider Ngarradj catchment should include parameters for different surface treatments on the mine site. It is proposed to use a portable rainfall simulator to collect runoff, infiltration and sediment loss data from disturbed and undisturbed sites on the ERA Jabiluka Mine site. Three replicates will be conducted on sites such as the cap of the waste rock dump, the batter slopes of the waste rock dump and undisturbed natural sites. Rainfall simulations are to be used in this study as the current intense stream monitoring program conducted in Ngarradj during the Wet season makes it logistically difficult to conduct plot monitoring. The simulator has been calibrated and successfully used during a 6 year project covering 14 central Queensland coal mines (R Loch pers comm 2000).

5.2.2 Spatial variability in SIBERIA

SIBERIA considers the landform evolution of a catchment through two main components, elevation variation and channel network development (Willgoose & Riley 1998). The model considers the elevation change and potential for channel network development on each cell within the DEM on which it operates. Spatial variability is included in SIBERIA's assessment of landform evolution through the definition of regions within the DEM for which individual sets of erosion and runoff parameters are applied. Regions are defined as individual files consisting of the x and y coordinates of the boundary of the region. The region boundary files remain constant throughout the simulation period. Each region has an associated set of erosion and runoff input parameters (β_1, m_1, n_1, β_3, m_3). The erosion parameters are stored in a single generic 'erode' file which subsequently relates to each region file, applying the particular set of parameters when SIBERIA operates on the defined region in the DEM.

The SIBERIA landform evolution model is a complex model that not only considers the parameters associated with a single cell, but also examines changes in the surrounding cells. That is, the erosion and runoff properties associated with a cell influence its elevation variation, which subsequently influences the direction in the which the output mass (or elevation) is moved to. Therefore, including parameter spatial variability in a SIBERIA landform evolution simulation does not simply result in the same landform development in the area described by a region for a single parameter simulation using the parameters prescribed for that region, but actually results in elevation changes that are influenced by surrounding regions (ie the whole is greater than the sum of the parts) (Ferguson 1999). However, the application of regions results in distinct boundaries where parameter values change abruptly. This trend is generally not demonstrated in nature with most soil properties changing gradually through space. This study will examine the effect of incorporating transitional parameters to represent the areas that exist between distinct landforms in order to approximate the gradual transition.

5.3 Sensitivity analysis of SIBERIA

Many hydrological and erosion modelling studies employ sensitivity analyses to methodologically investigate the response of selected output variables to variations in parameters and/or driving variables (Veihe & Quinton 2000). Sensitivity analysis studies are of particular importance in complex models, such as SIBERIA, as the model complexity frequently induces uncertainties in model output due to the propagation and compounding of errors in input parameter estimation through the modelling process. Sensitivity analysis provides a method by which model parameters can be ranked based on their contribution to overall error in model predictions. It describes model uncertainty because it indicates the expected errors in model prediction which will be attributable to errors in model parameters (Tiscareno-Lopez et al 1993). Furthermore, a detailed evaluation of a model's response can yield a great deal of insight into the nature of the model. In fact, to the degree of accuracy with which a model simulates a physical system, sensitivity analysis can provide considerable information on the influence of individual factors on the response of the physical system (Nearing et al 1990).

Uncertainty in the modelling process can be derived from three sources including structural uncertainty, parameter uncertainty and input uncertainty. Structural uncertainty refers to the inadequacy and the incompleteness of the model in accurately representing the physical system being studied. Parameter uncertainty arises from the uncertainty associated with parameters that are generally fixed in the model and not normally adjusted by the user. The final source of uncertainty, input uncertainty, refers to errors associated with the measurement or derivation of input data for the model (Chaves & Nearing 1991). This study will investigate the impact of input uncertainty on the SIBERIA modelling process.

Several sensitivity analysis methods exist ranging from simple analysis, where individual input variables and parameters are changed and the model output examined (De Roo 1996), to methods based on the Monte Carlo simulation, where a number of random parameter selections are made based on the input variables' probability distributions (Veihe & Quinton 2000). The Monte Carlo simulation method is suitable for complex non-linear models where the input parameters' probability distributions can be described and for models that involve the use of time-dependent driving variables (Tiscareno-Lopez et al 1993, Samper & Carrera 1995, Veihe & Quinton 2000). Through repeated numerical sampling from the input variables' probability distribution, a large number of samples of finite size are created. Estimation techniques are then applied to the samples and the distributions of the estimates are studies in relation to the true parameter values and to theoretical expectations about asymptotic distributions (Veihe & Quinton 2000).

The SIBERIA landform evolution model is being developed by the model's author to support Monte Carlo simulations. When the software packages have been modified, a quantitative risk assessment (QRA) study of the ERA Jabiluka Mine is proposed (G Willgoose pers comm 2000). The risk assessment will involve (a) the input of the error data into the new version of SIBERIA, (b) the running of the Monte Carlo simulations and (c) the analysis of the simulation output to determine the probability distribution of the desired environmental assessment. The computational demands of the proposed Monte Carlo simulation will be large. To put these demands in perspective, a 1000 year simulation using SIBERIA V8.10 of a 20 000 cell DEM (Willgoose & Riley 1998) takes about 30 minutes on a 500 MHz Pentium III running Windows 2000. Thus a 10 000 realisation simulation would take approximately 200 days. It is proposed that the runs will be done on a Tornado workstation cluster, which is optimised for doing large Monte Carlo simulations. This will allow the elapsed time to be reduced to about 10 days.

SIBERIA will not be modified to provide statistical analysis of the simulations as this would limit the analysis to those described in detail by the user prior to the Monte Carlo simulations being performed. Rather, results from all the simulations will be stored for later analysis in order to provide the most flexible approach to the final error analysis. However, this will require the availability of a very large amount of disk space. A considerable section of the final analysis will be conducted within the Ngarradj GIS.

The current estimation of the minimum number of realisations that should be considered is 10 000. However, it may be possible to reduce that number slightly once experience has been gained with some smaller test runs of the modified code. This estimate is based on a simple calculation in which the probability of failure was assumed to be 1 in 1000.

Table 13 shows the probability of observing no failures whatsoever in any of the realisations (ie the simulations would indicate that the project is acceptable when in fact it is not). Only with 10 000 simulations will the probability of saying something is acceptable, when in fact it is not, be acceptably low.

Table 13 Probability of having no failures for a set number of realisations (G Willgoose pers comm 2000)

Number of realisations	Probability of no failures
100	0.90
1000	0.37
10 000	4.5 e-5
100 000	3.5 e-44

5.4 Application to the assessment of mining impact

One of the primary advantages of linking environmental models to a GIS is the possibility of rapidly producing modified input-maps with different management practices to simulate alternative scenarios (De Roo 1996). Desmet and Govers (1995) for example, were able to rapidly assess the impact of varying a length proportionality factor on landform evolution within an agricultural landscape by using a GIS based simple landscape evolution model. The final objective to be achieved by this project is to apply the interactive GIS to the long-term assessment and management of possible impacts associated with the ERA Jabiluka Mine. The first step in this phase is therefore to identify the various management scenarios that are possibly going to be applied to the ERA Jabiluka Mine. The draft Environmental Impact Statement (EIS) for the Jabiluka uranium mine project (Kinhill 1996) provides descriptions of mine development alternatives. These include the Ranger Mill Alternative (RMA), the Jabiluka Mill Alternative (JMA) and the Pancontinental proposal.

Once the GIS/modelling technology has been developed and elevation models for each of these management alternatives obtained, various scenarios of mine site design will be modelled to assess possible impacts of the ERA Jabiluka Mine on landform evolution within the Ngarradj catchment. It is expected that these model simulations will focus on the final development alternatives, for example JMA, addressing various design scenarios incorporated in the alternative such as waste rock dump and infrastructure design variation. Impacts of the alternative management scenarios on catchment evolution will be assessed over both long- and short-term time scales. Outcomes derived from these modelling scenarios can be used in the formation of management recommendations once final decisions on mine development and design are made. The application of the interactive GIS to real life problems will aid the identification of possible problems associated with the interactive GIS. This will allow the opportunity to refine the tool and will give an understanding of any potential application limitations.

6 Conclusions

Since their inception, GIS have evolved and are still evolving from simple graphical tools towards being fully developed 'intelligent' systems. A GIS is currently being used by ***eriss*** as a central management tool to coordinate the storage, manipulation and retrieval of information generated by an investigation into the geomorphological impacts of the ERA Jabiluka Mine, Northern Territory, Australia. Data useful to the project are disparate in terms of location, format and the original context in which it was collected. GISs have the unique ability to store, manage and manipulate these highly variable datasets, providing an environment that eliminates problems such as absence of metadata and multiple copies of the same datasets spread through an organisation.

However, although the range of functionality offered by GIS is continually expanding, GIS still lack the full functionality of environmental modelling and statistical data analysis packages commonly used in geomorphological analyses. A GIS centred approach to data management, therefore, retains the data storage, manipulation and retrieval powers of GIS whilst maintaining a degree of flexibility that allows the full use of functionality contained within other software packages. Developing a GIS through which all facets of the geomorphologic impact assessment processes are linked allows a more holistic analysis and explanation of both geomorphic baseline studies and modelling outcomes. Implementation of this approach also allows the simplification of data maintenance, revision and update as well as facilitating availability and access for users.

Soil erosion hazard models form an important first step in investigating erosion patterns within a catchment. GIS-based erosion hazard models allow the user to rapidly investigate the impact of different land use and soil conservation scenarios on a erosion patterns within a catchment. This study has included the evaluation of a relatively simple, GIS-based rapid erosion risk assessment method using recently acquired data for the Ngarradj catchment. Input data required by the rapid erosion assessment approach can be derived from widely available land unit and elevation datasets. The use of the AUSLIG 1:250 000 relief and hydrology dataset, as opposed to land units elevation data, as an elevation data source was found to greatly improve the validity of the rapid erosion assessment approach. The rapid erosion assessment method represents an effective means for quickly acquiring and evaluating existing data to assist in the planning and implementation of more detailed monitoring and modelling programs.

A preliminary evaluation of integrated hydrology/landform evolution modelling techniques and GIS for assessing the possible impacts of mining on the Ngarradj catchment has been conducted. Hydrology and sediment transport parameters were derived from field data collected within the Ngarradj catchment. The derived hydrology parameters were used in the DistFW hydrology model to predict annual hydrographs in order to determine long-term hydrology parameters required by the SIBERIA landform evolution model. The predicted annual hydrographs were also used with the sediment transport parameters to derive annual sediment loss values for SIBERIA. This preliminary assessment of landform evolution in the Ngarradj catchment demonstrates the complex process associated with the parameterisation of the SIBERIA model.

Initial attempts to link the hydrology and landform evolution models with GIS have indicated that the parameter derivation and modelling process can be simplified by the integration of these technologies. Linking these models with GIS provides significant advantages as the GIS assists in the derivation, storage, manipulation, processing and visualisation of geo-referenced data at a catchment wide scale. Through the rapid production of modified input scenarios, it is anticipated that linking the landform evolution model with GIS will provide a valuable tool for assessing the possible impacts of mining impact on catchment sedimentary and hydrological processes.

The quantification of changes in basin morphology over time represents a significant challenge when conducting an analysis of landuse impact on landform evolution. A suite of geomorphic statistics have been adapted for implementation within a GIS. The hypsometric curve, width function and cumulative area diagram have been shown in this report to be suitable for quantifying landform evolution and therefore can be used to assess the impact of various landuse scenarios on landform evolution. The area-slope relationship, however, was not found to be a sensitive statistic to landform evolution in the Ngarradj catchment. This has been attributed to the complex geomorphology of the Ngarradj catchment.

Additional research is required to develop a more fully integrated GIS and landform evolution modelling approach that is beneficial for the pro-active management of mining and more wide ranging catchment management scenarios. The incorporation of spatial variability in input parameter values in the SIBERIA modelling process will be further facilitated through linking the model with a GIS. Application of the integrated system to investigate the impact of the ERA Jabiluka Mine on landform evolution in the Ngarradj catchment will provide valuable information for the long-term management of the mine as well providing feed-back on the efficacy and user-friendliness of the system. However, the propagation of error and uncertainty through the modelling process must also be investigated in order to provide estimates of model output reliability.

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