



**Application of
geographic
information systems
to the assessment
and management
of mining impacts**

**Progress Report 2
RUSLE and SIBERIA based
assessments of erosion
in the Swift Creek Catchment**

G Boggs, K Evans & C Devonport

August 2000

Environmental Research Institute of the Supervising Scientist (*eriss*)

Internal Report 336

**Application of GIS to the Assessment and Management of
Mining Impact: Progress Report 2**

**RUSLE and SIBERIA based Assessments of Erosion in the
Swift Creek Catchment**

Prepared by

Guy Boggs⁺⁺, Ken Evans⁺ and Chris Devonport^{*}

Northern Territory University

Darwin NT 0909

Environmental Research Institute of the Supervising Scientist

Locked Bag 2, Jabiru NT 0886

August 2000

Relevant Files - JR - 05 - 327

SG2000/0016

SG2000/0090

CONTENTS

| | |
|--|-----------|
| Foreword | 1 |
| Study A: Rapid Assessment of Erosion Risk in a Small Catchment in the Wet/Dry Tropics of Australia Using GIS. | 3 |
| A1.0 INTRODUCTION | 3 |
| A2.0 AIMS | 4 |
| A3.0 Study Area | 5 |
| A4.0 RAPID ASSESSMENT MODEL | 7 |
| A5.0 DATA | 8 |
| A6.0 DERIVATION OF RUSLE FACTORS | 10 |
| A6.1 RUSLE Soil Erodibility Factor | 10 |
| A6.2 RUSLE Slope Gradient Factor | 13 |
| A6.3 RUSLE Slope Length Factor | 14 |
| A6.4 RUSLE Cover Management Factor | 15 |
| A7.0 RESULTS AND VALIDATION | 16 |
| A7.1 Elevation Data Resolution | 16 |
| A7.2 Field Data Validation | 23 |
| A8.0 CONCLUSION | 25 |
| Study B: Assessing Catchment-wide, Mining Related Impacts on Sediment Movement in the Swift Creek Catchment, Northern Territory, Australia, Using GIS and Landform Evolution Modelling Techniques | 27 |
| B1.0 Introduction | 27 |
| B2.0 Study Area | 30 |
| B3.0 Database Establishment | 31 |
| B4.0 Siberia Input Parameter Derivation | 34 |
| B4.1 DISTFW Hydrology Model | 35 |
| B4.2 Sediment Transport Model | 39 |
| B4.3 Scale analysis - Discharge area relationship | 40 |
| B4.4 Runoff series and long-term sediment loss rate | 41 |
| B4.5 Slope correction | 43 |
| B5.0 GIS Linkage | 43 |
| B5.1 DISTFW Hydrology Model | 43 |
| B5.2 SIBERIA Landform Evolution Model | 46 |
| B6.0 Application | 47 |
| B7.0 Conclusions | 51 |
| References | 53 |

Figures

Study A

| | |
|--|----|
| Figure A1: The location of the ERA Jabiluka Mine and Swift Creek catchment in the Northern Territory of Australia | 6 |
| Figure A2: The landunits of the Swift Creek catchment | 9 |
| Figure A3: The total methodology involved in the implementation of the rapid erosion assessment approach within a GIS | 11 |
| Figure A4: A flow chart depicting the methodology used in the derivation of the soil erodibility grids..... | 13 |
| Figure A5: The slope grid derived from the 25m grid cell resolution Swift Creek DEM..... | 14 |
| Figure A6: A flow chart representing the processes, replicated for each DEM, used in the derivation of the final flow length grids..... | 15 |
| Figure A7: The distribution of erosion risk throughout the Swift Creek catchment, calculated solely using the land units data | 17 |
| Figure A8: The relative soil erosion risk distribution for the Swift Creek catchment calculated using data from the 100m DEM | 20 |
| Figure A9: The relative soil erosion risk distribution for the Swift Creek catchment calculated using data from the Swift Creek 25m DEM..... | 21 |
| Figure A10: The relationship between relative soil loss and area for both the measured and predicted values..... | 25 |

Study B

| | |
|--|----|
| Figure B1: A flow diagram depicting the processes involved in the parameterisation of the SIBERIA landform evolution model. | 29 |
| Figure B2: The location of the ERA Jabiluka Mine and Swift Creek catchment in the Northern Territory, Australia. | 30 |
| Figure B3: The approach used in the development of a GIS as a focus point for datasets generated during the geomorphologic impact assessment of the ERA Jabiluka Mine. | 32 |
| Figure B4: Conceptual view of the DISTFW rainfall-model (after Willgoose and Riley, 1998). | 36 |
| Figure B5: Rainfall/Discharge of selected events | 37 |
| Figure B6: An example of a predicted hydrograph produced by DISTFW compared with the observed hydrograph. | 38 |
| Figure B7: The peak discharge/area relationship exhibited by the field data..... | 41 |
| Figure B8: Differences in elevation, indicating areas of erosion and deposition, between the Swift Creek catchment at 0 years and after being modelled for a period of 500 years. | 48 |

Tables

Study A

| | |
|--|----|
| Table A1: Soil erodibility factors, Kf (field adjusted K), for different combinations of soil texture and organic matter (Mitchell and Burbenzer, 1980) | 12 |
| Table A2: Soil properties of the land units of the Swift Creek catchment..... | 12 |
| Table A3: Slope statistics for the Swift Creek catchment, calculated using land units, a 100m resolution DEM and a 25m resolution DEM..... | 14 |
| Table A4: The qualitative descriptions of soil and vegetation cover provided by Wells (1979) and the corresponding cover management factor (Ca) value derived for this project. | 16 |
| Table A5: The percentage area represented by each erosion risk class for each scale of analysis. | 17 |
| Table A6: The relationship between erosion risk, calculated solely using land units data, and land unit. | 18 |
| Table A7: The proportion of each land unit occupied by the 100m DEM predicted relative erosion risk classes. | 20 |
| Table A9a) A correlation matrix for the 100m DEM and Land Units erosion risk grids; b) the 100m and 25m erosion risk grids and; c) the Land Units and 25m erosion risk grids. | 22 |
| Table A10: Sediment delivery ratios and measured (both unadjusted and SDR adjusted) and predicted soil loss ratios between the sampled sub-catchments | 24 |

Study B

| | |
|---|----|
| Table B1 : The observed and predicted discharges for the 1998/1999 wet season in the Swift Creek catchment..... | 39 |
| Table B2: Long-term average soil loss, uncorrected for node scale, for the Swift Creek catchment | 42 |
| Table B3: Descriptions of the tools developed to facilitate the automatic generation of the topographic input requirements of the DISTFW hydrology model..... | 45 |
| Table B4: General statistics for the Swift Creek catchment at 100 year intervals between 0 and 500 years. | 49 |

Acknowledgments

The authors would like to thank Mr M. Saynor and Mr D. Moliere, (*eriss*) for their advice on the field sampling program and landform evolution modelling respectively. We are grateful to Mr B. Smith and Mrs E. Crisp (*eriss*) for their assistance in the collection of the field data. We are also grateful to Drs G. Hancock (University of Newcastle) and S. Timms (*eriss*) for their computer programming advice.

Note

This report is the third report prepared for the collaborative research project entitled 'Application of Geographic Information Systems to the Assessment and Management of Mining Impact'. Previous reports relating to this project are:

Internal Report 320 – Application of Geographic Information Systems to the Assessment and Management of Mining Impact: A Project Outline

Internal Report 327 – Application of Geographic Information Systems to the Assessment and Management of Mining Impact: Progress Report 1 – Initial GIS Development

Foreword

Construction of the portal, retention pond and other headworks for the ERA Jabiluka Mine commenced in June 1998. The catchment of the Swift Creek, 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 ERA Jabiluka Mine. In February, 1999, a research project was established to develop a GIS that interacts with sediment transport, hydrology and landform evolution modelling techniques for use in the long term 'total catchment management' of Swift Creek. This report represents the second progress report prepared for this collaborative research project established by *eriss* and the Northern Territory University and covers the work conducted during the period January to July, 2000. Within this period two distinct studies were conducted. The first study, entitled '*rapid assessment of erosion risk in a small catchment in the wet/dry tropics of Australia using GIS*', evaluates a GIS and RUSLE based rapid erosion assessment in the Swift Creek catchment. The second study entitled '*assessing catchment-wide, mining related impacts on sediment movement in the Swift Creek catchment, Northern Territory, Australia, using GIS and landform evolution modelling techniques*' provides a preliminary assessment of a significantly more complex and sophisticated landform evolution model linked to a GIS.

Assessing the impact of various land uses on catchment erosion processes commonly requires in depth research, monitoring and field data collection, as well as the implementation of sophisticated modelling techniques. The first study in this report (Study A) describes the evaluation of a GIS based rapid erosion assessment method, which allows the user to quickly acquire and evaluate existing data to assist in the planning of more detailed monitoring and modelling 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. The rapid erosion assessment method proves to be a valuable tool that is highly useful as an initial step in the planning of more detailed erosion assessments

Preliminary linking of a sophisticated landform evolution model (SIBERIA) with a GIS has been completed and tested on a catchment-wide basis for long-term total catchment management. The second study in this report (Study B) represents the first attempt to apply the model on a catchment wide basis in the region. Linking the model with a GIS enhances the modelling process as the GIS assists in the derivation, storage, manipulation, processing and visualisation of geo-referenced data at a catchment wide scale. This preliminary assessment of landform evolution in the Swift Creek catchment demonstrates the complex process associated with the parameterisation of the SIBERIA model and illustrates the benefits of integrating GIS with landform evolution modelling techniques. Additional research is required to develop a more integrated GIS and landform evolution modelling approach to assessing the possible impacts of mining on catchment sedimentary and hydrological processes.

Study A: Rapid Assessment of Erosion Risk in a Small Catchment in the Wet/Dry Tropics of Australia Using GIS.

A1.0 INTRODUCTION

The Environmental Research Institute of the Supervising Scientist (*eriss*) carries out independent research into the environmental effects of uranium mining. The Rehabilitation of Mine Sites (RMS) group at *eriss* are concerned, *inter alia*, with gauging the impact of mining on catchment geomorphologic processes and landform evolution in mineral leases within the boundaries of the world heritage Kakadu National Park (KNP). This assessment requires extensive in depth research, monitoring and collection of data in the field, and sophisticated modelling techniques 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. The development and application of a rapid assessment technique for the purpose of assessing one aspect of landform evolution, namely erosion, is the subject of this paper.

Erosion is the combined effect of a number of significant land forming factors. It is necessary to understand and quantify the natural erosion processes in a given environment before the impact of activities such as mining can be assessed (Lane et al, 1992). It is also important to identify areas of risk at the start of a monitoring program so that different risk categories are monitored appropriately. Erosion models represent an efficient means of investigating the physical processes and mechanisms governing soil erosion rates and amounts. Soil erosion models have particularly important roles in soil resource conservation and non-point source assessments as they allow land managers to predict the soil erosion impacts of various land uses and management practices before they are implemented. (Lane et al, 1992). Much of the soil erosion research and model development has been directed at agricultural landscapes dominated by temperate climates. The area of interest to RMS, on the other hand, is natural environments in the wet-dry tropics of Australia.

Linking erosion simulation models with GIS provides a powerful tool for land management. Utilising GIS in erosion assessment allows the rapid production of modified input-maps, increasing the efficiency with which various scenarios can be modelled. Large catchments can be modelled within a GIS with greater detail and the results more easily interpreted as they are commonly represented as maps. Once entered into a GIS, data can be easily modified and can be obtained and converted from a number of GIS formats (De Roo, 1996). The ability of GIS to provide a detailed description of the catchment morphology through DEMs also greatly benefits soil erosion modelling (Mitas and Mitasova, 1998). However, it should be stressed that 'absolute values' provided by soil erosion models are merely estimations of soil loss. The primary advantage of soil erosion modelling therefore arises from the relative comparison of estimations based on different scenarios (Pilesjo, 1992).

Puig *et al.* (2000) explored the possibility of developing a GIS based approach for rapidly assessing erosion within the wet/dry tropics of northern Australia. Research by Puig *et al.* investigated the potential of modifying the Universal Soil Loss Equation (USLE) (Wischmeier *et al.*, 1958; Wischmeier and Smith, 1978), a well known and widely used soil erosion model, to enable a rapid assessment of erosion risk. The approach described by Puig *et al.* primarily relies on the use of land units classification data, which are readily available within the Northern Territory. However, the investigation by Puig *et al.* was limited by both time and available data. These limitations resulted in the USLE being over simplified and the robustness and predictions of the modified model not being evaluated.

A2.0 AIMS

This paper describes a rapid assessment of erosion risk within the Swift Creek catchment, Northern Territory, using the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1994). 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 rapid erosion assessment approach to be validated. More precisely, the aims of this paper are to;

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

A3.0 STUDY AREA

The Swift Creek catchment, known locally as Ngarradg Creek, is located approximately 230 km east of Darwin and approximately 20 km north of the town of Jabiru (Figure A1). The Swift Creek catchment lies partly in the Jabiluka Mineral Lease (JML) and partly in the surrounding Kakadu National Park (KNP), and contains the Jabiluka Uranium 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 almost 43 square kilometres. Within the catchment two distinct landform regions are represented, an upland plateau region with highly dissected sandstone and shallow sandy soils and the Swift Creek 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 is approximately 1450 mm, 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).

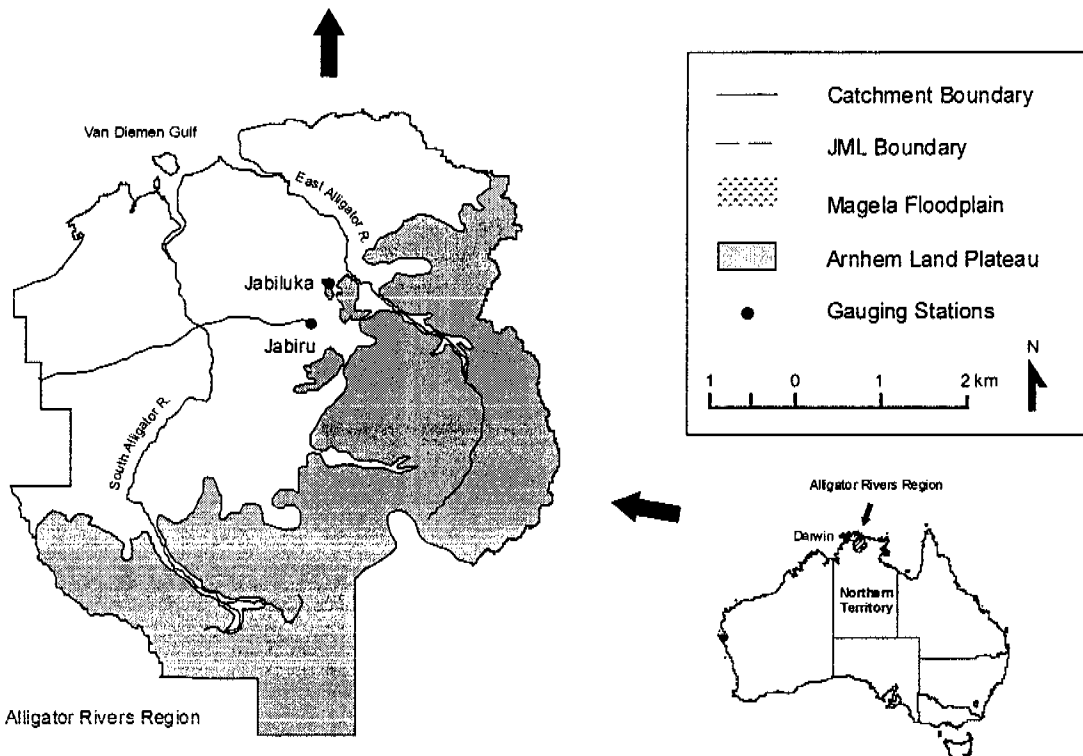
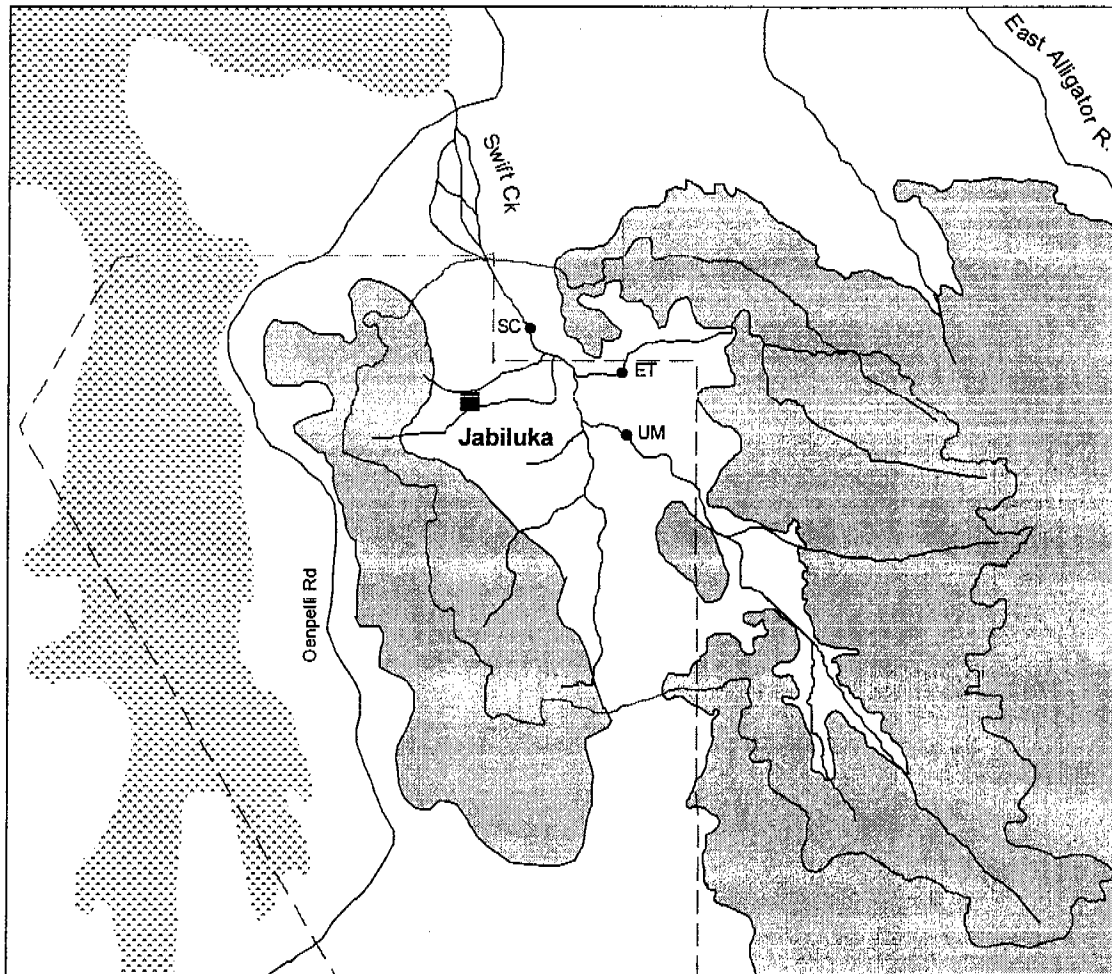


Figure A1: The location of the ERA Jabiluka Mine and Swift Creek catchment in the Northern Territory of Australia

A4.0 RAPID ASSESSMENT MODEL

The RUSLE is an updated form of the USLE, which has been developed from extensive datasets collected in agricultural situations in the USA. As such, the RUSLE, in its absolute form, is not a mathematical tool that can be used 'straight out of the box' when applied to new environments. However, when the erosion assessment is simplified to identifying relative erosion risk the equation can be more easily adapted to new situations. Hudson (1973) relates how the USLE was successfully simplified to;

(A1)

$$A = K \times S \times C$$

This approach is considered to represent the minimum number of factors that can be used during a relative erosion assessment. The exclusion of the remaining R, L and P factors can be justified for a relative assessment model in a small natural catchment on the following basis (Puig *et al.*, 2000):

- (i) R, the rainfall erosivity index, reflects the energy content of the rain. Regardless of the actual value of R this variable remains constant within an area of similar annual rainfall. R can therefore be ignored, as it will not be responsible for any variation in erosion within the Swift Creek catchment.
- (ii) L, the slope length factor, is generally considered to be a highly complex factor to calculate when the model is applied to entire catchments. This complexity, and the fact that soil loss is less sensitive to slope length than to any other factor, results in the L factor commonly being ignored in catchment scale studies.
- (iii) P, the support practice, in a natural environment is 1. P can therefore be removed from the equation.

The soil erodibility factor, the cover factor and the slope factor were consequently determined to be the essential factors required for the initial rapid assessment model. However, integrating the USLE with a GIS provided the possibility of rapidly calculating the slope length from DEM data. As the slope length factor represents the change in the erosive power of accumulating water over a specified distance, slope length could be represented by the longest upslope distance along the flow path. This distance is calculated from each location to the top of the drainage divide. The slope length factor was therefore included in the final rapid assessment model, such that;

(A2)

$$A = K \times S \times L \times C$$

The primary issue associated with implementing a rapid assessment approach is the availability of suitable data. Data must be easily accessible and in a readily useable form in order to facilitate the adoption of a rapid assessment approach. A review of existing and available data revealed that estimated values for the factors described in equation A2 could be obtained from the widely available digital land unit descriptions of Wells (1978) and the AUSLIG elevation data. The model described in equation A2 and the data provided by these two data sources, forms the basis of the rapid assessment approach.

A5.0 DATA

A key issue associated with implementing the rapid erosion assessment approach is data availability. However, there is commonly a trade off between data availability and data accuracy/resolution. Data obtained for this project consists of land unit data mapped at a 1:50000 scale (Wells, 1978), a DEM with a grid cell resolution of 100m and a DEM with a grid cell resolution of 25m. The land units map of Wells, shown in Figure A2, 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. The land unit descriptions include information that is directly relevant in an RUSLE based rapid erosion assessment, including slope gradients, soil descriptions and vegetation community classifications. It is widely accepted that the spatial coverage of soil and vegetation can be represented by classifications of relatively homogenous areas. However, elevation related variables, including slope angle, are commonly regarded as being too spatially variable to be grouped into broad classifications. Furthermore, the land units descriptions do not provide information on slope length. For these reasons, a rapid erosion assessment based solely on the land units classification is being contrasted with erosion assessments based on both the land units data and increasingly higher resolution DEMs.

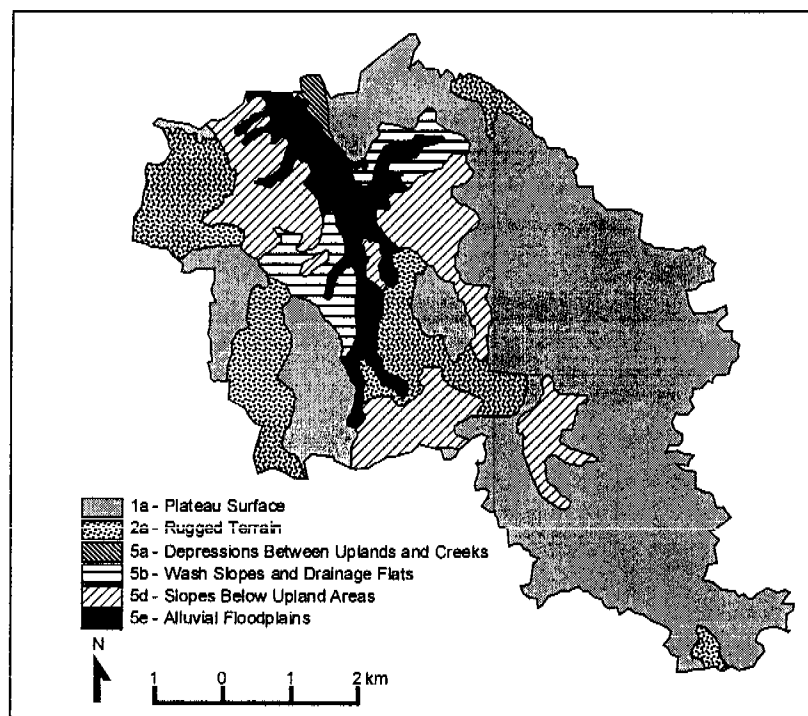


Figure A2: The landunits of the Swift Creek catchment

Resolution is amongst the most important DEM attributes and will determine the usefulness and cost of a DEM. A DEM was interpolated at a 100m grid cell resolution using the original Australian Surveying and Land Information Group (AUSLIG) 1:250 000

relief and hydrology data. These data are widely available throughout the Northern Territory. The interpolation algorithm used in the formation of 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). A DEM obtained for the Swift Creek catchment, derived from 1:25000 aerial photography and produced on a 25m grid was also used to assess the validity of the data derived from the land units classification and 100m DEM data in the rapid assessment approach.

A6.0 DERIVATION OF RUSLE FACTORS

Implementation and verification of the rapid erosion assessment approach developed within this study was performed within a GIS on a grid cell basis (Figure A3). A number of different methods were employed in the preparation of the factors described in equation A2 in order to assess and refine the implementation method of the rapid assessment model described above. The methods used in the derivation of the various factor values and datasets are described below.

A6.1 RUSLE Soil Erodibility Factor

The dominant soils found within the Swift Creek catchment vary substantially from the shallow lithosol soils associated with areas of sandstone upland plateau to the deep sands of the floodplain alliance. The land unit descriptions of Wells (1979) 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. Mitchell and Bubenzer (1980) have produced a table from which agricultural K values can be established using various combinations of soil texture and organic matter content (Table A1). This table was used to derive the soil erodibility factor values for the land units of the Swift Creek catchment (Table A2).

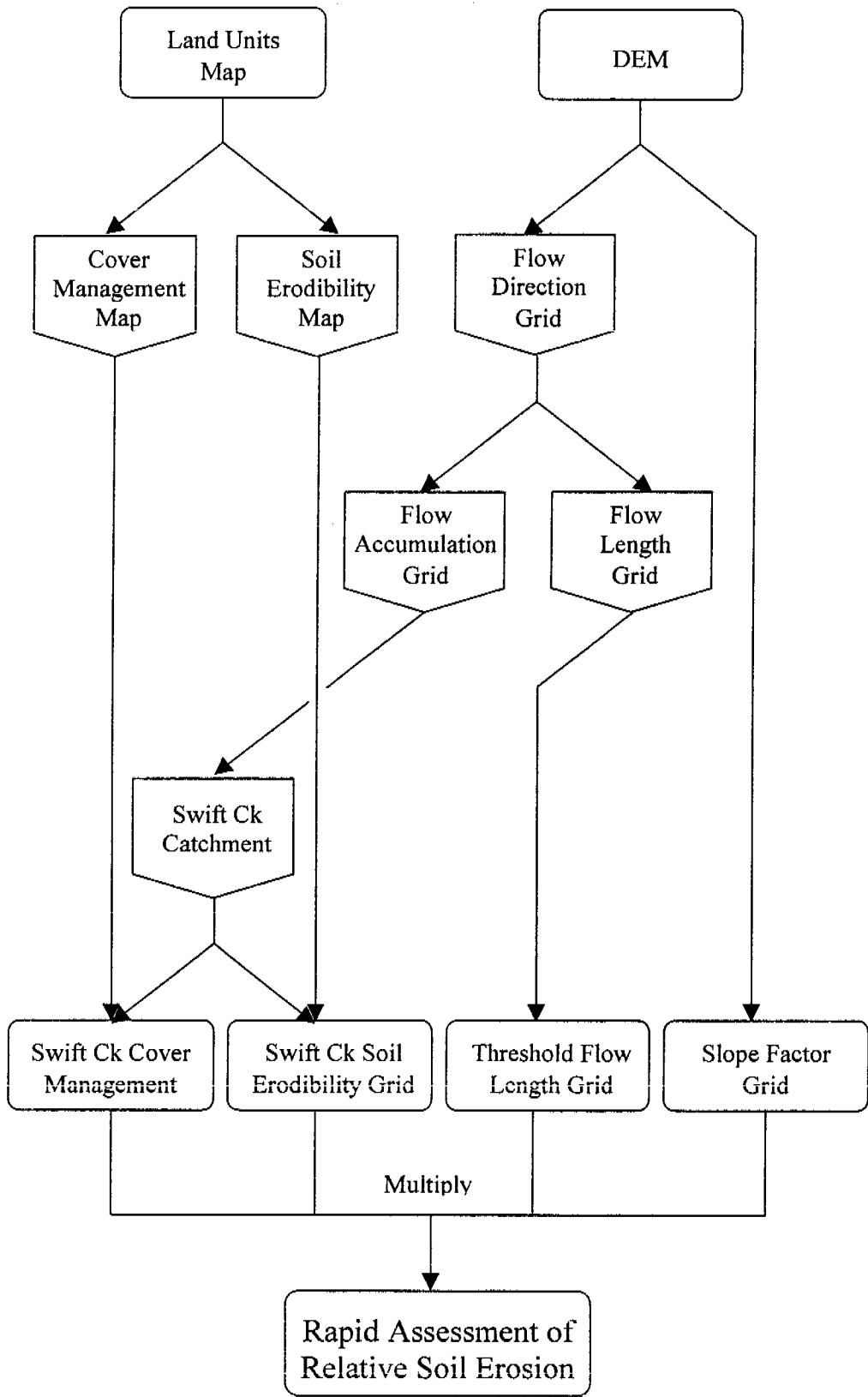


Figure A3: The total methodology involved in the implementation of the rapid erosion assessment approach within a GIS.

Table A1: Soil erodibility factors, K_f (field adjusted K), for different combinations of soil texture and organic matter (Mitchell and Burbenzer, 1980)

| Texture Class | Organic | Matter | Content |
|----------------------|----------------|----------------|----------------|
| | <0.5% | 2% | 4% |
| | K _f | K _f | K _f |
| Sand | 0.05 | 0.03 | 0.02 |
| Fine sand | 0.16 | 0.14 | 0.1 |
| Very fine sand | 0.42 | 0.36 | 0.28 |
| Loamy sand | 0.12 | 0.1 | 0.08 |
| Loamy fine sand | 0.24 | 0.2 | 0.16 |
| Loamy very fine sand | 0.44 | 0.38 | 0.3 |
| Sandy loam | 0.27 | 0.24 | 0.19 |
| Fine sandy loam | 0.35 | 0.3 | 0.24 |
| Very fine sandy loam | 0.47 | 0.41 | 0.33 |
| Loam | 0.38 | 0.34 | 0.29 |
| Silt loam | 0.48 | 0.42 | 0.33 |
| Silt | 0.6 | 0.52 | 0.42 |
| Sandy clay loam | 0.27 | 0.25 | 0.21 |
| Clay loam | 0.28 | 0.25 | 0.21 |
| Silty clay loam | 0.37 | 0.32 | 0.26 |
| Sandy clay | 0.14 | 0.13 | 0.12 |
| Silty clay | 0.25 | 0.23 | 0.19 |
| Clay | 0.13 | 0.22 | 0.29 |

Table A2: Soil properties of the land units of the Swift Creek catchment

| Land | Dominant Soil | % | K |
|------|---------------------------------|-------|------|
| Unit | | OM | |
| 1a | Shallow lithosols | <0.5% | 0.05 |
| 2a | Shallow lithosols | <0.5% | 0.05 |
| 5a | Deep earthy sands | 4% | 0.08 |
| 5b | Moderately deep siliceous sands | <0.5% | 0.16 |
| 5d | Moderately deep siliceous sands | <0.5% | 0.16 |
| 5e | Alluvial soils or sands | 2% | 0.13 |

The methodology used in the production of the final various resolution soil erodibility grids is shown in Figure A4. The catchment boundary coverage used to clip the soil erodibility coverage was derived, in each case, from the DEM of the same resolution (where the land units data were modelled at a resolution of 25m).

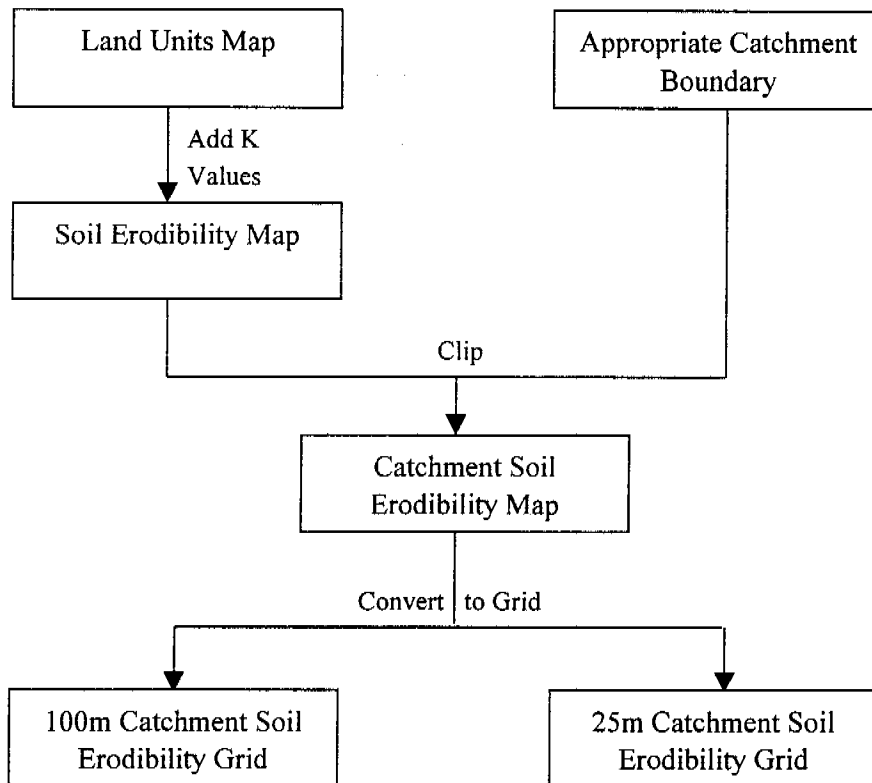


Figure A4: A flow chart depicting the methodology used in the derivation of the soil erodibility grids.

A6.2 *RUSLE Slope Gradient Factor*

The slope angle factor was calculated for the land units coverage and each DEM. To derive the slope angle factor from the land units coverage, the maximum slope contained within each land unit description was expressed as a decimal and attached as an attribute to the land unit coverage. This coverage was then converted to a grid with a cell size of 25m. The function utilised in the production of the slope grids from the two DEMs 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 each slope angle calculation covered an area greater than that of the Swift Creek catchment. This allows for the flattening effect which occurs when the slope function is applied to cells at the edge of a grid. An example of a

final slope grid is shown in Figure A5. The comparative slope statistics for each final slope angle factor grid are shown in Table A3.

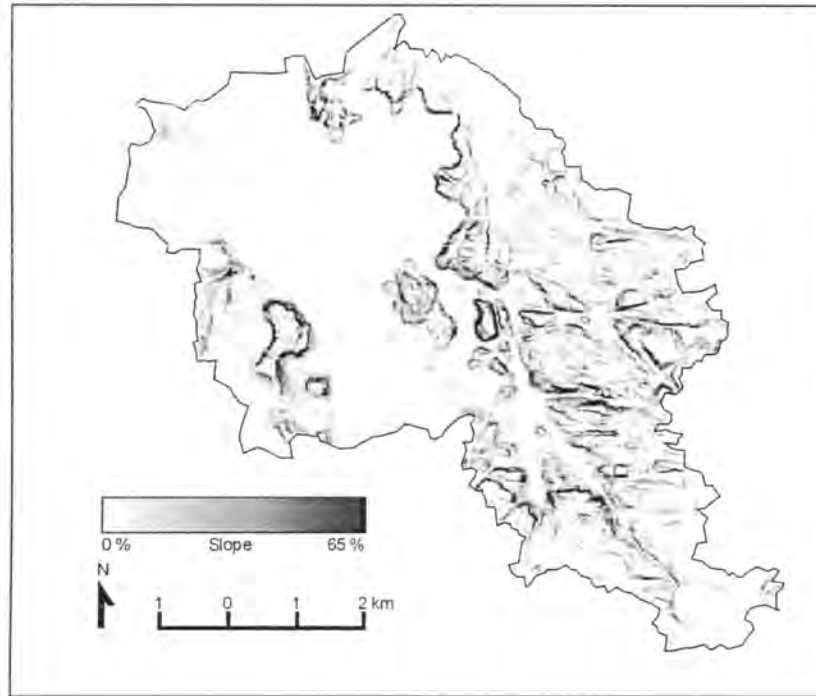


Figure A5: The slope grid derived from the 25m grid cell resolution Swift Creek DEM.

Table A3: Slope statistics for the Swift Creek catchment, calculated using land units, a 100m resolution DEM and a 25m resolution DEM.

| | Maximum | Minimum | Mean |
|------------|---------|---------|-------|
| Land Units | 0.40 | 0.02 | 0.125 |
| 100m DEM | 0.26 | 0.00 | 0.06 |
| 25m DEM | 0.65 | 0.00 | 0.11 |

A6.3 *RUSLE Slope Length Factor*

The *RUSLE* slope length factor was approximated for each DEM by calculating the longest upslope distance along the flow path for each grid cell (Figure A6). This function operates by considering the direction of flow of each cell upstream of its location, and determining the longest distance. Within an erosion risk assessment, areas containing stream channels are generally associated with a relatively high potential for erosion. A threshold was therefore applied to the accumulated flow length, with flow lengths greater than 1

kilometre considered to be operating under fluvial conditions and assigned the maximum value of 1. As with the K, S and C factors, the slope length factor grid therefore consisted of values between 0 and 1.

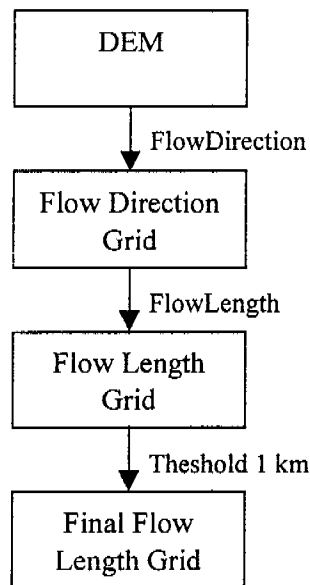


Figure A6: A flow chart representing the processes, replicated for each DEM, used in the derivation of the final flow length grids.

A6.4 *RUSLE Cover Management Factor*

The USLE 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 (1979) provides qualitative descriptions of both the soil's surface condition and vegetation cover. A cover index (C.I.), 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 A4). This relative estimation of the cover management factor was found to be sufficient when providing a rapid, relative assessment of soil loss. The process used to derive the final cover management factor grids to be input into the rapid erosion assessment model is equivalent to that used in the derivation of the soil erodibility factor grids (Figure A4).

Table A4: The qualitative descriptions of soil and vegetation cover provided by Wells (1979) and the corresponding cover management factor (Ca) value derived for this project.

| Unit | Soil cover | Vegetation | C.I. | C _a (1/C.I.) |
|------|--------------------------------|--------------------------------------|------|----------------------------|
| 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 |

A7.0 RESULTS AND VALIDATION

A7.1 Elevation Data Resolution

The rapid erosion assessment model described in this study was implemented using three elevation data sources in order to contrast the effects of using land units data or increasingly higher resolution DEMs on assessing erosion risk. However, as the land units data contains no information on slope length the rapid erosion assessment model implemented using this data source was simplified to that described by Hudson (1973) (equation A1). The final implementation of the rapid erosion assessment model therefore differed for the land units data and the DEM data. The resultant soil loss grids from all analyses were classified into areas of relatively low, moderate and high erosion risk. The thresholds used in the definition of these erosion risk classes were selected through analysis of all resultant soil loss grids and were chosen to maximise the variability captured by the three classes. The percentage of the total catchment area occupied by each erosion class is shown in Table A5.

Table A5: The percentage area represented by each erosion risk class for each scale of analysis.

| Resolution | Low Risk (%) | Moderate Risk (%) | High Risk (%) |
|------------------|--------------|-------------------|---------------|
| Land Units Slope | 71 | 15 | 14 |
| 100m Interp. DEM | 39 | 55 | 6 |
| 25m Swift DEM | 68 | 29 | 3 |

The spatial distribution of erosion risk classes calculated using the land units data is shown in Figure A7. As would be expected, using the land units data to derive all the RUSLE model input parameters caused the pattern in the spatial distribution of erosion risk classes to correspond with those displayed by the original land unit data. Correlations have been drawn between the land unit and predicted erosion risk in Table A6.

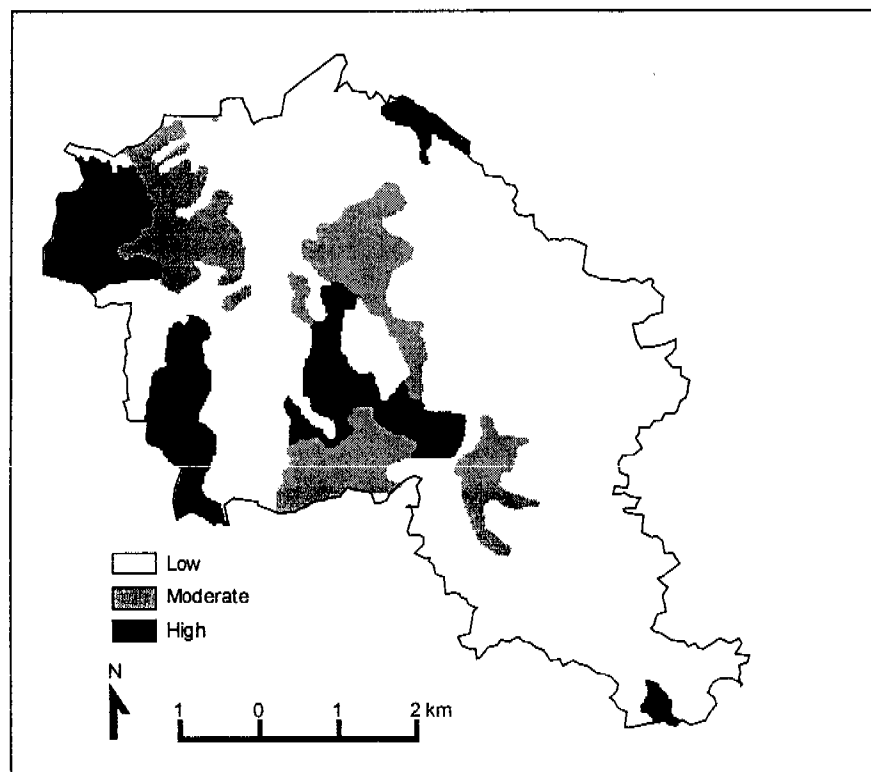


Figure A7: The distribution of erosion risk throughout the Swift Creek catchment, calculated solely using the land units data

Table A6: The relationship between erosion risk, calculated solely using land units data, and land unit.

| Low | Moderate | High |
|-----|----------|------|
| 1a | 5d | 2a |
| 5a | | |
| 5b | | |
| 5e | | |

The areas of highest erosion risk correspond with the 2a land unit ('rugged terrain'). This land unit has both low soil erodibility and cover index values, indicating that the high degree of slope associated with these areas greatly effects the predictions of the simplified RUSLE. However, these areas include the escarpment face, separating the plateau surface landunit from the floodplain alliance land units. The escarpment face and area immediately below are either composed of solid rock or covered in boulders. These areas would therefore be expected to have very low erosion potential, despite the large slope angles. The inability of the land unit data to identify the difference in erosion potential between the escarpment and slope areas of this land unit is a significant issue when attempting to model erosion risk throughout a catchment. This error impacts on the classification of other land units in a relative assessment. Of prime importance is the classification of erosion potential in the land unit 5d as moderate. The 5d land unit occupies the sloping area between the 2a land unit and the creek lines. These areas have poorly coherent soils, are sloping and located below high discharge zones. These characteristics make this land unit highly susceptible to erosion.

Another issue with this method is associated with the exclusion of the slope length factor from the analysis. That is, as the slope length is increased there is a greater chance of concentrated flow, and therefore a greater risk of erosion. Land units 5a, 5b and 5e are located on relatively deep, sandy soils and contain the floodplain drainage lines. The areas directly around these drainage lines would be highly susceptible to erosion and should be

allocated a higher erosion risk value. It is not possible to derive this information solely from the land units data.

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 the efficacy of a DEM. The application of equation A2 using data derived from the 100m grid cell resolution DEM produced a more spatially distributed estimation of soil loss than solely using land units data (Figure A8). The proportion of each land unit occupied by the predicted relative erosion risk classes is shown in Table A7. The erosion risk values obtained using this method appear to correlate well with the land unit descriptions of Wells. That is, the high erosion risk areas tend to be concentrated within the land unit 5d, which, as previously described, contains areas that are highly susceptible to erosion. The upland plateau, composed of highly resistant sandstone, contains the majority of the low erosion potential class.

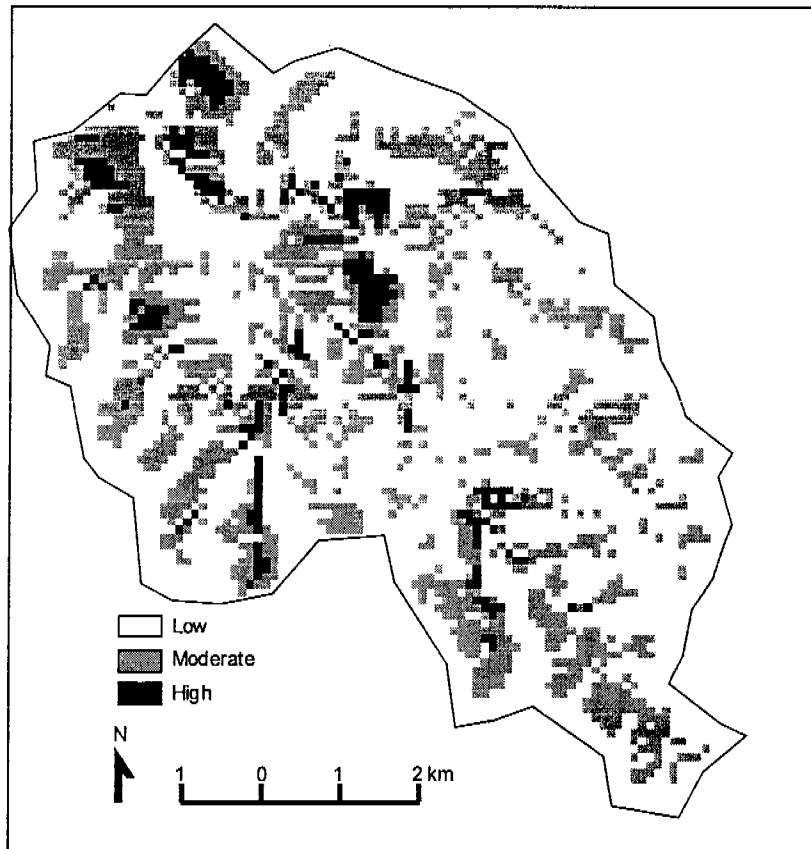


Figure A8: The relative soil erosion risk distribution for the Swift Creek catchment calculated using data from the 100m DEM

Table A7: The proportion of each land unit occupied by the 100m DEM predicted relative erosion risk classes.

| | 1a | 2a | 5a | 5b | 5d | 5e |
|----------|-----|-----|-----|-----|----|----|
| Low | 42 | 10 | < 1 | 2 | 5 | 4 |
| Moderate | 18 | 4 | < 1 | 1 | 6 | 2 |
| High | < 1 | < 1 | < 1 | < 1 | 3 | 1 |

The Swift Creek DEM, captured from 1:25000 aerial photography and produced at a resolution of 25m, provides a more detailed representation of the Swift Creek catchment. The erosion risk predicted using this DEM within the rapid erosion assessment model is therefore calculated and presented at a greater level of detail (Figure A9). However, the predictions made using these data do not correlate highly with the land unit descriptions. Most significantly, the greatest proportion of high risk values are associated with the land unit 1a, whilst the land unit 5d is dominated by low erosion risk values (Table A8). This

discrepancy is most likely attributable to the smoothing effect of increasing cell size causing areas of high slope to become highlighted during an erosion assessment using larger resolution DEMs. (Garbrecht and Martz, 1994). Although this relationship may be correct in many parts of the world, within the Swift Creek catchment areas of high slope are generally located around the edge of or within the 1a land unit and are therefore predominantly composed of outcropping sandstone. This issue could be resolved through the use of a slope threshold to delineate areas not likely to have a soil covering (ie outcropping sandstone) and therefore of low erosion risk. However, this issue also emphasises the need for soil erodibility and soil cover datasets at a scale more comparable to the Swift Creek DEM during more comprehensive erosion assessments.

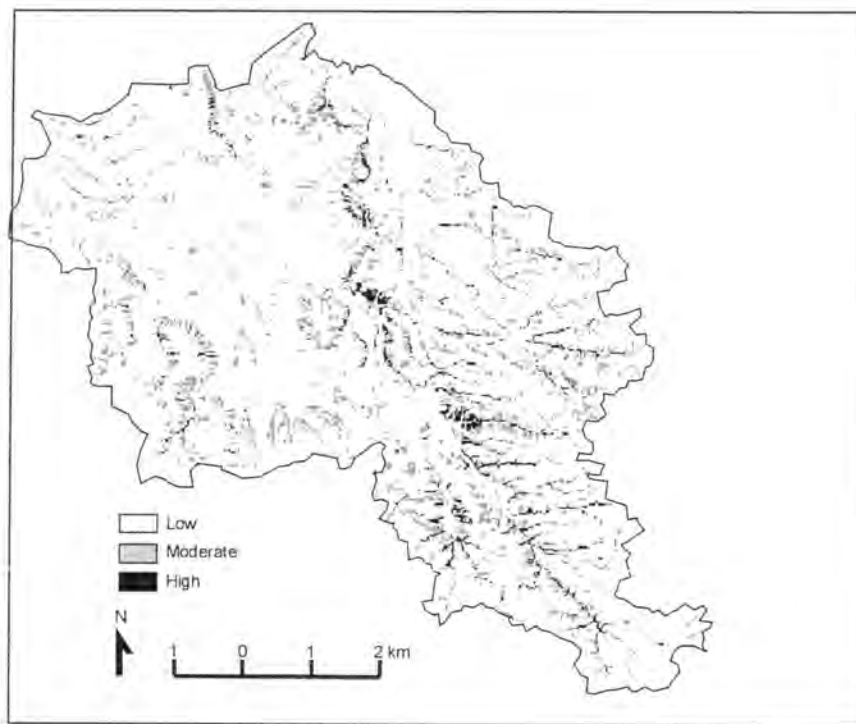


Figure A9: The relative soil erosion risk distribution for the Swift Creek catchment calculated using data from the Swift Creek 25m DEM

A series of correlation matrices were produced to establish the magnitude of differences that existed between the three output grids of soil erosion risk (Table A9a, A9b, A9c). Differences between the 100m and land units soil erosion grid, shown in table A9a, are

predominantly associated with the estimation of moderate values in the 100m erosion grid in locations where low values have been assigned in the land units erosion grid, and the estimation of low values in the 100m erosion grid where high values are found in the land units erosion grid. This pattern is similarly shared between the 25m and land units erosion grids. Differences between the 100m and 25m erosion grids, on the other hand, are dominated simply by alternative classifications of moderate and low erosion risk values. These differences indicate that the land units erosion grid is significantly different from the DEM derived erosion grids, whilst differences between the 25m and 100m erosion grids are less substantial.

Table A9a) A correlation matrix for the 100m DEM and Land Units erosion risk grids; b) the 100m and 25m erosion risk grids and; c) the Land Units and 25m erosion risk grids.

| A) | | 100m DEM | | |
|------|--------------|----------|--------------|----------|
| | | Low (%) | Moderate (%) | High (%) |
| Land | Low (%) | 45 | 23 | 3 |
| | Moderate (%) | 6 | 6 | 3 |
| | High (%) | 10 | 4 | < 1 |

| B) | | 100m DEM | | |
|---------|--------------|----------|--------------|----------|
| | | Low (%) | Moderate (%) | High (%) |
| 25m DEM | Low (%) | 42 | 21 | 4 |
| | Moderate (%) | 18 | 11 | 2 |
| | High (%) | < 1 | < 1 | < 1 |

| C) | | Land Units | | |
|---------|--------------|------------|--------------|----------|
| | | Low (%) | Moderate (%) | High (%) |
| 25m DEM | Low (%) | 48 | 9 | 11 |
| | Moderate (%) | 21 | 5 | 3 |
| | High (%) | 1 | < 1 | < 1 |

A7.2 Field Data Validation

The RMS group at *eriss* have established a field project to collect baseline geomorphological data on catchment geomorphology, channel stability, sediment movement and hydrology of the Swift Creek catchment (Boggs *et al.*, 1999). 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 (Figure A1). Two stations are located upstream of all mine influences, the first on the main right bank tributary of the Swift Creek ('East Trib') and the second on the main Swift Creek channel ('Up Main'). The third station ('Swift Creek') is downstream of the minesite. 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 Swift Creek. 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 A10). However, the measured sediment yields had to be modified as it has long been recognised that only a fraction of the sediment eroded within a stream's catchment will be transported to the basin outlet, as sediment is deposited in temporary and permanent stores within the catchment itself (Walling, 1983). This relationship can be quantified as a sediment delivery ratio (SDR) by calculating the percentage of the annual gross erosion that is measured as the sediment yield at the basin outlet. Approximations of the SDRs for each of the Swift Creek sub-catchments were obtained using the relationship between SDR and drainage basin area developed by the U.S. Soil Conservation Service (Walling, 1984) and SDR values obtained for smaller

catchments (0.15 – 0.78 km²) within the Alligator Rivers Region by Duggan (1988) (Table A10). 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 A10).

Table A10: Sediment delivery ratios and measured (both unadjusted and SDR adjusted) and predicted soil loss ratios between the sampled sub-catchments

| | East Tributary | Up Main | Swift Ck |
|------------------|----------------|---------|----------|
| SDRs | 18 % | 15 % | 12 % |
| Measured Yield | 1 | 1.49 | 1.81 |
| Adjusted for SDR | 1 | 1.79 | 2.71 |
| Land units | 1 | 2.46 | 6.78 |
| 100m Interp DEM | 1 | 2.13 | 5.07 |
| 25m Swift DEM | 1 | 3.76 | 6.4 |
| Catchment Area | 1 | 2.25 | 5.12 |

The ratio of sediment loss between the East Tributary, Up Main and Swift Ck sub-catchments is shown in Table A10 for both field measured and predicted values. Sediment yields, adjusted using approximations of each sub-catchment's SDR, indicate that there is a log-linear relationship between catchment area and sediment loss within the Swift Creek catchment. This log-linear relationship is also shown by the rapid erosion assessment based on the 25m Swift Creek DEM (Figure A10). 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 Up Main and Swift Creek sub-catchments. The most accurate prediction of erosion in the East Tributary sub-catchment, relative to the measured soil loss, was made using the 100m interpolated DEM (Table A10). However, the relative sediment loss is overpredicted using this dataset for the Swift Creek sub-catchment, with a linear relationship between area and relative sediment loss displayed in these predicted values. An almost exponential relationship is shown by values predicted using the rapid erosion assessment approach and land units dataset. These results indicate that the rapid erosion assessment method tends to be increasingly influenced by

area with decreasing data resolution, with a general underprediction of net erosion over smaller areas and overprediction in larger areas.

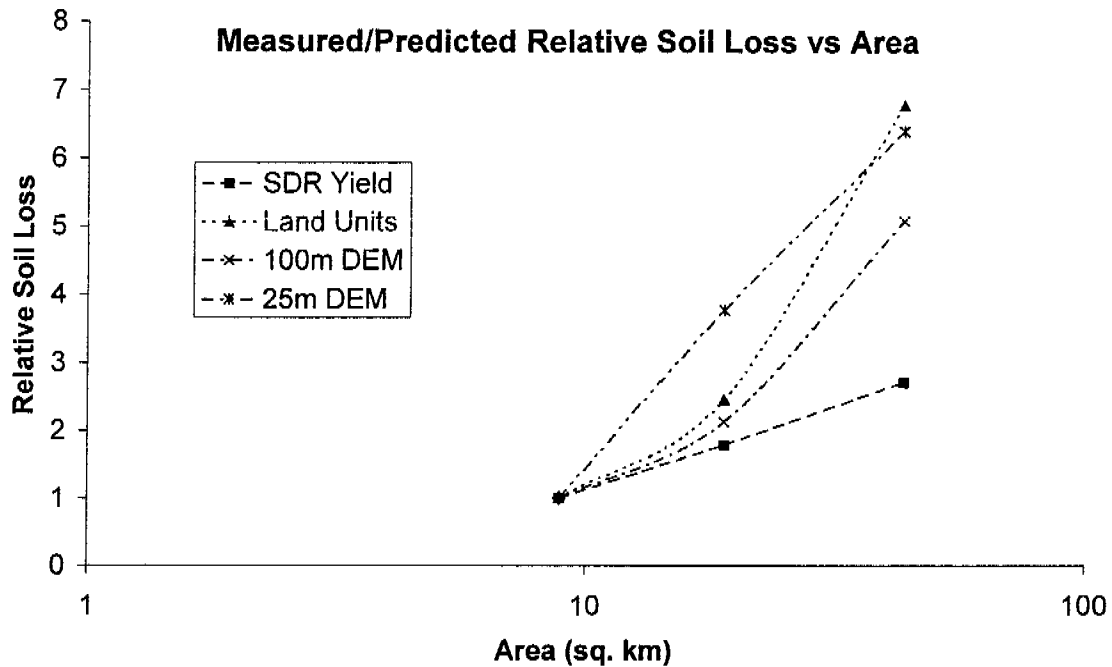


Figure A10: The relationship between relative soil loss and area for both the measured and predicted values.

A8.0 CONCLUSION

Linking or incorporating soil erosion models in GIS provides powerful research tools for calculating the effects of land use changes and evaluating soil conservation scenarios on a catchment scale. However, environmental models are commonly complex and data intensive. This study has evaluated a relatively simple, rapid erosion risk assessment method using recently acquired data for the Swift Creek catchment, Northern Territory, Australia. 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 1:250000 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. Elevation data captured at a significantly higher resolution did not greatly enhance the erosion assessment, emphasising the need for soil erodibility and soil cover datasets at a

comparable scale during more comprehensive erosion assessments. The comparison of predicted soil loss ratios with measured in-stream sediment yields on a sub-catchment basis indicated that the rapid erosion assessment method tends to be increasingly influenced by area with decreasing data resolution. However, it must be remembered that the rapid erosion assessment method simply represents a means for quickly acquiring and evaluating existing data to assist in the planning and implementation of more detailed monitoring and modelling programs.

Study B: Assessing Catchment-wide, Mining Related Impacts on Sediment Movement in the Swift Creek Catchment, Northern Territory, Australia, Using GIS and Landform Evolution Modelling Techniques

B1.0 INTRODUCTION

The impact of mining activities on complex and relatively poorly understood environments represents a significant issue facing decision-makers in northern Australia. In June 1998, construction of the portal, retention pond and other headworks for the ERA Jabiluka Mine (ERAJM), Northern Territory, commenced. Swift Creek, a major downstream right bank tributary of the Magela Creek and associated floodplain is located in the World Heritage and RAMSAR listed Kakadu National Park and will be the first catchment to be affected should any impact occur as a result of mining operations at the ERAJM. Recent research has addressed the development of a geographic information system (GIS) that interacts with sediment transport, hydrology and landform evolution modelling techniques for use in long-term total catchment management. This paper provides a description of the spatial database established and the GIS tools constructed and processes utilised, so far, to facilitate the linkage and integration of GIS with a hydrology model, sediment transport model and landform evolution model. This paper presents examples of the application of these GIS tools and geomorphological models to catchment management through the preliminary assessment of future landform evolution in the Swift Creek catchment.

Environmental models attempt to simulate spatially distributed, time variable environmental processes (Steyaert, 1993). GIS, through their ability to capture,

manipulate, process and display geo-referenced data, are able to describe the spatial environment (Burrough and McDonnell, 1998). GIS and environmental modelling are therefore complementary and the overlap and relationship between these technologies is clearly apparent (Fedra, 1993). Since GIS and environmental modelling have evolved separately they have different data structures, functions and methods for the input and output of spatial information (Maidment, 1996). Over the past two decades there has been considerable research into the integration of these two methodologies to the extent that the synthesis of spatial data representations and environmental models has been described as the new 'Holy Grail' (Raper and 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 the analysis of model output, to closely integrated systems (Charnock et al., 1996).

SIBERIA, the landform evolution model used in this study, is a sophisticated three-dimensional topographic evolution model. The model has been used to investigate post-mining rehabilitated landform design at the Energy Resources of Australia (ERA) Ranger Mine since 1993 (Willgoose and Riley, 1993, Evans, 1997, Evans et al., 1998, Willgoose and Riley, 1998, Evans, 2000). To date the model has only been used to examine landform evolution on post-mining rehabilitated landforms. This project is the first attempt to apply the model on a catchment wide basis in the region. Research will investigate whether the shift from mine-site scale modelling of landforms to catchment scale modelling of mining impact can be facilitated by the linkage of the landform evolution model with a GIS. Linking the model with a GIS will greatly enhance the modelling process as the GIS can assist in the derivation, storage, manipulation, processing and visualisation of geo-referenced data at a catchment wide scale.

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 (Figure B1). An extensive field data collection program provides data on catchment sediment movement and hydrology of Swift Creek, allowing the direct calibration of these models.

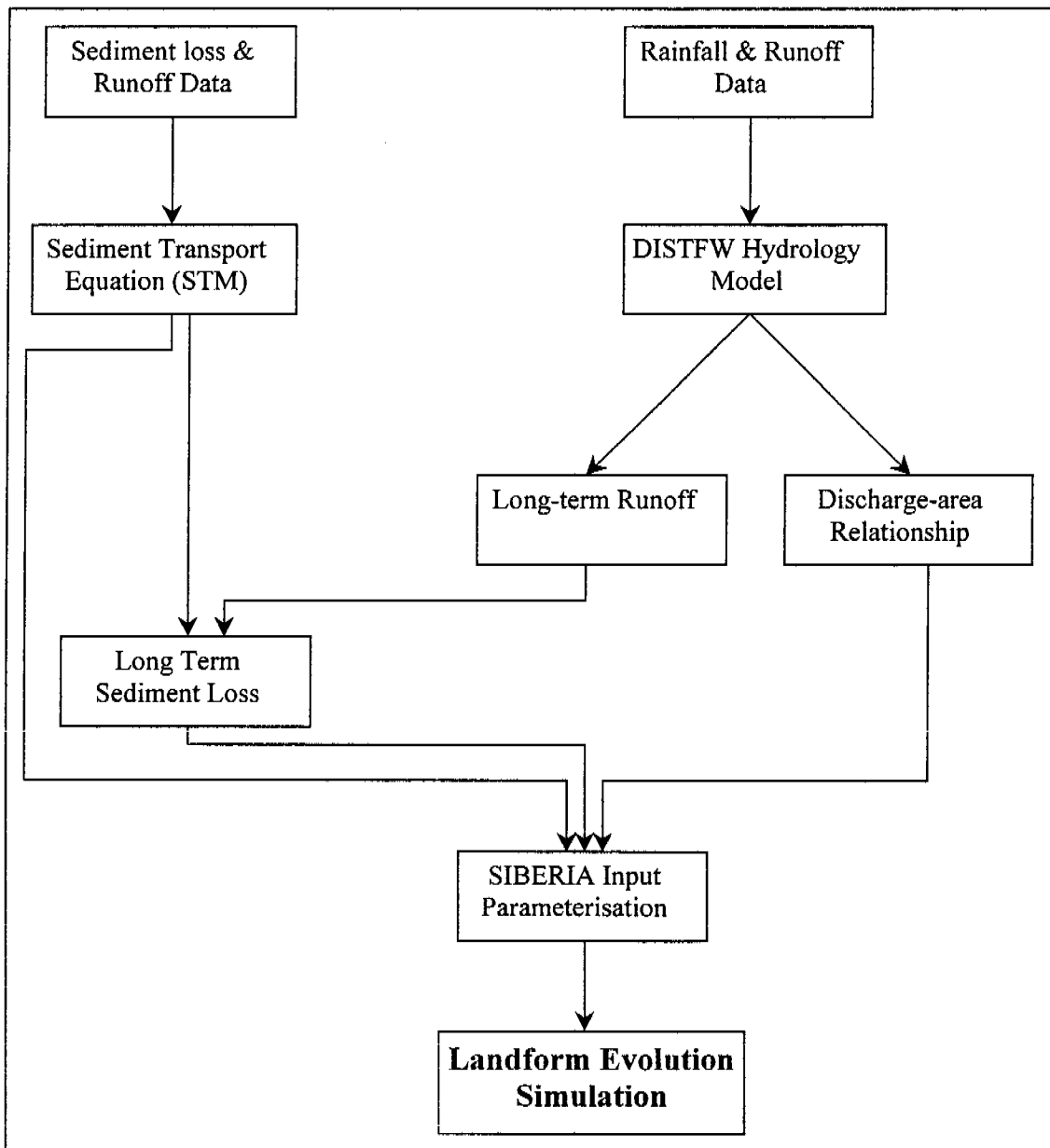


Figure B1: A flow diagram depicting the processes involved in the parameterisation of the SIBERIA landform evolution model.

B2.0 STUDY AREA

The Swift Creek catchment is located approximately 230 km east of Darwin and 20 km north-east of the town of Jabiru (Figure B2). The Swift Creek catchment lies partly in the Jabiluka Mineral Lease (JML), partly in the surrounding Kakadu National Park (KNP), and contains the ERAJM 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 almost 46 km² (Figure B2).

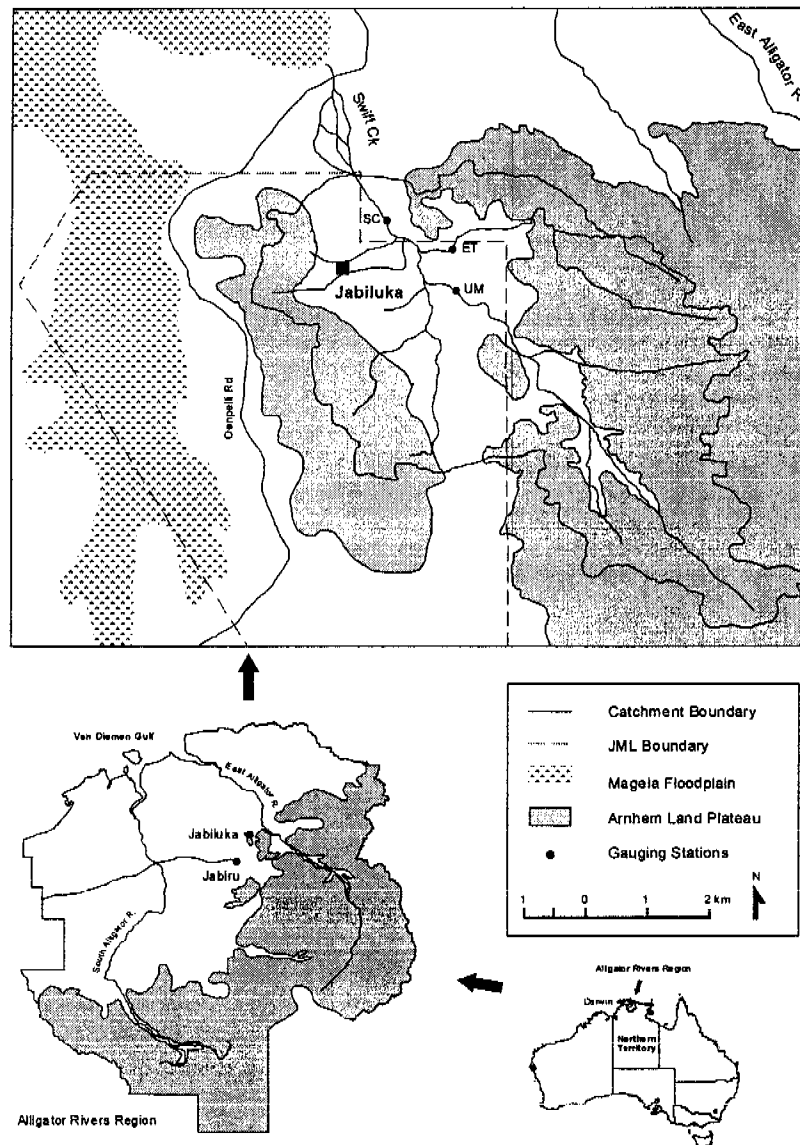


Figure B2: The location of the ERA Jabiluka Mine and Swift Creek catchment in the Northern Territory, Australia.

Two distinct landform regions are represented within the catchment. The upland plateau region occupies the eastern, southern and western sections of the catchment and consists of highly dissected sandstone, shallow sandy soils and exposed rock. The central and northern sections of the catchment contain the Swift Creek floodplain which is generally flat and covered by deep sandy soils. Located in the monsoon tropics climatic zone, the catchment experiences a distinct wet season from October to April and a dry season for the remainder of the year. The average annual rainfall is approximately 1450 mm. Perhaps more importantly for landform evolution is the high rainfall intensity associated with wet season storms, with events of 100 mm/hr for a duration of 10 minutes expected to occur annually (Finnegan, 1993).

B3.0 DATABASE ESTABLISHMENT

Data acquired from the field program are varied and include information on catchment geomorphology, channel stability, sediment movement and hydrology of the Swift Creek catchment. The methods and processes required to store, retrieve and manipulate the datasets resulting from impact assessment are diverse, ranging from individual spreadsheets and statistical analysis to spatial databases and visual analysis. Data emanating from this project can be grouped into five categories, based on these methods and processes; (1) High Temporal Resolution Spreadsheet Data, (2) Low Temporal Resolution Spreadsheet Data, (3) Raster Data, (4) Vector (dGPS) Data and (5) Model Data. A database has been established that employs GIS as a framework for these datasets, retaining the flexibility and functionality required to store and manipulate each dataset individually, whilst offering a central hub for project data (Figure B3) (Boggs et al., In Press).

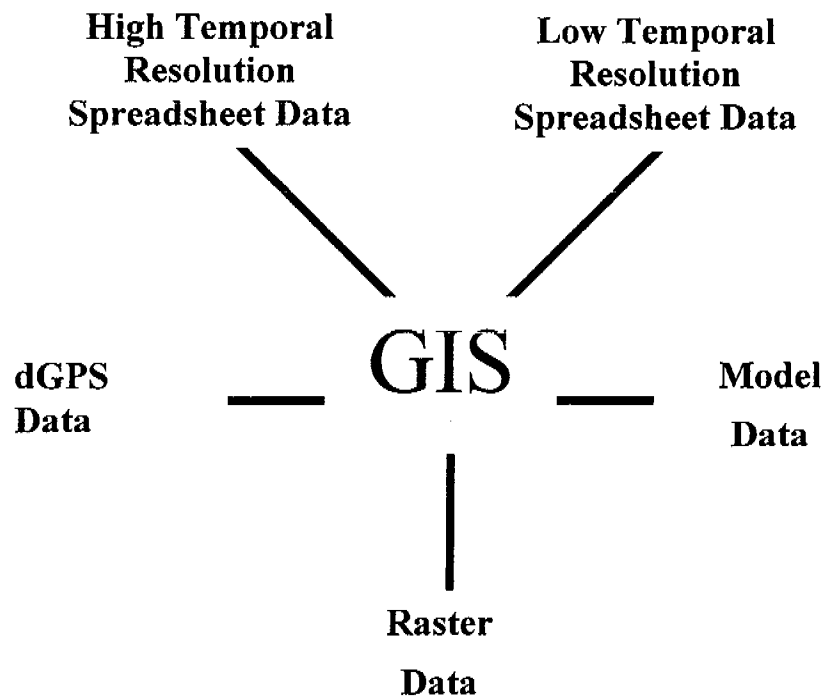


Figure B3: The approach used in the development of a GIS as a focus point for datasets generated during the geomorphologic impact assessment of the ERA Jabiluka Mine.

As part of the field program, three stream gauging sites have been established. Two stations are located upstream of all mine influences, on the main right bank tributary of the Swift Creek ('East Tributary') and on the main Swift Creek channel ('Upper Main'). The third station ('Swift Creek Main') is located on the main Swift Creek channel downstream of the mine site and can be used to assess potential impacts from the mine site (Figure B2). The western branch of Swift Creek is braided and cannot be gauged. It is assumed that any variation in sediment loads at the downstream Swift Creek site not reflected at the two upstream sites result from mine site impact. Data collected at each station include rainfall, discharge and sediment loss. Rainfall is recorded at 6-minute intervals at each station using a 0.2mm tipping bucket. Water level information is also collected at 6-minute intervals using a shaft encoder. A rating

curve, established from manual discharge gaugings undertaken weekly, is used to convert water level information to stream discharges. Each station has been located on relatively well-vegetated, stable stream sections, providing consistent cross-sections from which an accurate rating table has been produced. Suspended sediment data are collected weekly.

The existing *eriss* spatial database contains approximately 12Gbytes of data, including thematic coverages, aerial photography, satellite imagery and elevation data. The base GIS contains the topographic 1:250000 digital data produced by AUSLIG (which includes layers of drainage, waterbodies, roads etc.) with some of the data available at 100K scale. Additional data layers are related to individual projects and have been obtained in the field or from aerial photography or other imagery (Bull, 1999).

A digital elevation model (DEM), interpreted from 1:25 000 aerial photography of the region and produced on a 5m grid, has been captured for the entire Swift Creek catchment and will form the basis of much of the hydrological and erosion modelling. One of the advantages of using DEM data in hydrological and geomorphological studies is that spatially variable information can be obtained, as opposed to the more common point data (eg rain gauges) (Schultz, 1993). DEMs are currently used in many geomorphologic studies as they allow the extraction of terrain and drainage features to be automated and have been used to delineate drainage networks and watershed boundaries, calculate slope characteristics and produce flow paths of surface runoff (Moore et al., 1991, Quinn et al., 1992).

B4.0 SIBERIA INPUT PARAMETER DERIVATION

SIBERIA predicts the long-term evolution of channels and hill slopes in a catchment (Willgoose et al., 1991). The model solves for two variables; (1) elevation, from which slope geometries are determined, and (2) an indicator function that determines where channels exist. The evolving drainage system of a catchment can be modelled.

SIBERIA predicts the long-term average change in elevation of a point by predicting the volume of sediment lost from a node on a DEM. Fluvial sediment transport rate through a point (q_s) is determined in SIBERIA by the following equation:

$$q_s = \beta_1 q^{m_1} S^{n_1} \quad (\text{B1})$$

where: q_s = sediment flux/unit width, S = slope (m/m), q = discharge ($\text{m}^3 \text{y}^{-1}$), and β_1 = sediment transport rate coefficient. Parameters m_1 and n_1 are fixed by flow geometry and erosion physics.

SIBERIA does not directly model discharge (Willgoose et al., 1989) but uses a sub-grid effective parameterisation based on empirical observations and justified by theoretical analyses which conceptually relates discharge to area (A) draining through a point as follows (Leopold et al., 1964):

$$q = \beta_3 A^{m_3} \quad (\text{B2})$$

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 .

To obtain the parameter values for Equations (B1) and (B2) it is necessary to:

1. calibrate a hydrology model using rainfall-runoff data from field sites

2. fit parameters to a sediment transport equation using data collected from field sites, and
3. derive long-term average SIBERIA model parameter values for the landform being modelled.

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 parameters of SIBERIA represent temporally averaged properties of the processes occurring on the landscapes. The parameter values derived for the sediment transport and the DISTFW rainfall-runoff models represent instantaneous values (Willgoose and Riley, 1993) and must be integrated over time to yield the temporally averaged values.

The SIBERIA input parameter derivation process (steps 1 to 3 above) as described below is based on the description given by Willgoose and Riley (1993).

B4.1 DISTFW Hydrology Model

The Distributed parameter Field-Williams (DISTFW) hydrology model is a sub-catchment based rainfall-runoff model that uses a one-dimensional kinematic wave flood routing model called the Field-Williams Generalised Kinematic Wave Model (Field and Williams, 1983; 1987). Willgoose and Riley (1993), Finnegan (1993) and Arkinstal et al (1994) have described the model and its application to mine spoils and waste rock in detail. DISTFW has been used to generate parameters required by the SIBERIA landform evolution model (eg. Evans et al., 1998; Willgoose and Riley, 1998). DISTFW divides a catchment into a number of sub-catchments connected with

a channel network draining to a single catchment outlet. Hortonian runoff is modelled and drainage through sub-catchments is represented by a kinematic wave on the overland flow. The kinematic assumption that friction slope equals the bed slope is used and discharge is determined from the Mannings equation. The hydrological processes represented by the model are shown in Figure. B4.

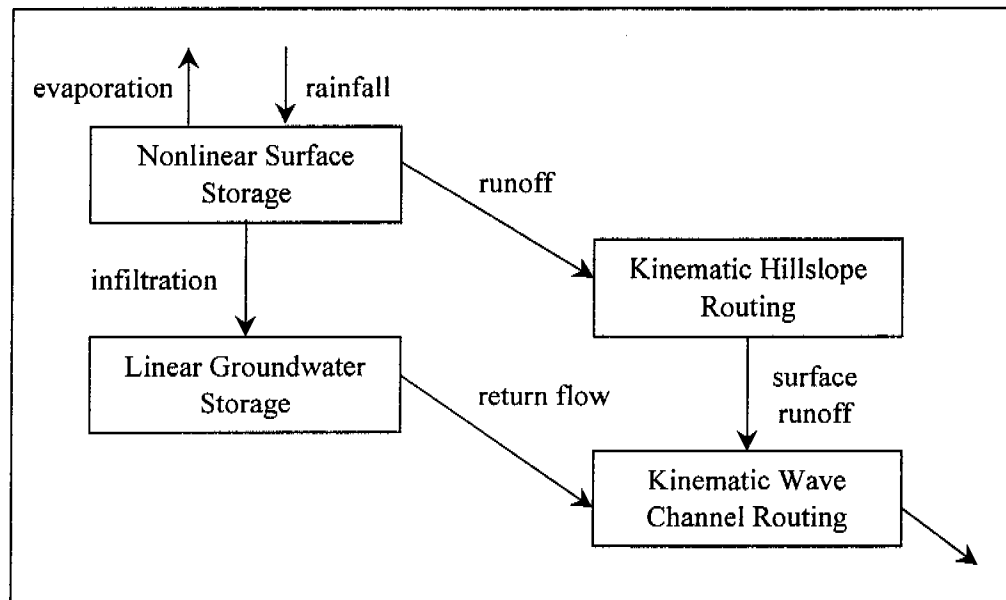


Figure B4: Conceptual view of the DISTFW rainfall-model (after Willgoose and Riley, 1998).

The calibration process for the DISTFW hydrology model involves using a non-linear regression package, NLFIT, to fit model parameter values (Willgoose et al., 1995).

The parameters fitted in this preliminary study were:

- sorptivity (initial infiltration) - S_{phi} ($\text{mm h}^{-0.5}$),
- long-term infiltration - ϕ (mm h^{-1}), and
- kinematic wave coefficient and exponent, - c_r ($\text{m}^{(3-2e_m)}\text{s}^{-1}$) and e_m .

Calibration of the DISTFW hydrology model involves fitting parameters for selected storm events. The average rainfall, calculated from the data collected at each of the gauging stations, was plotted with discharge for the Swift Creek 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 (Figure B5).

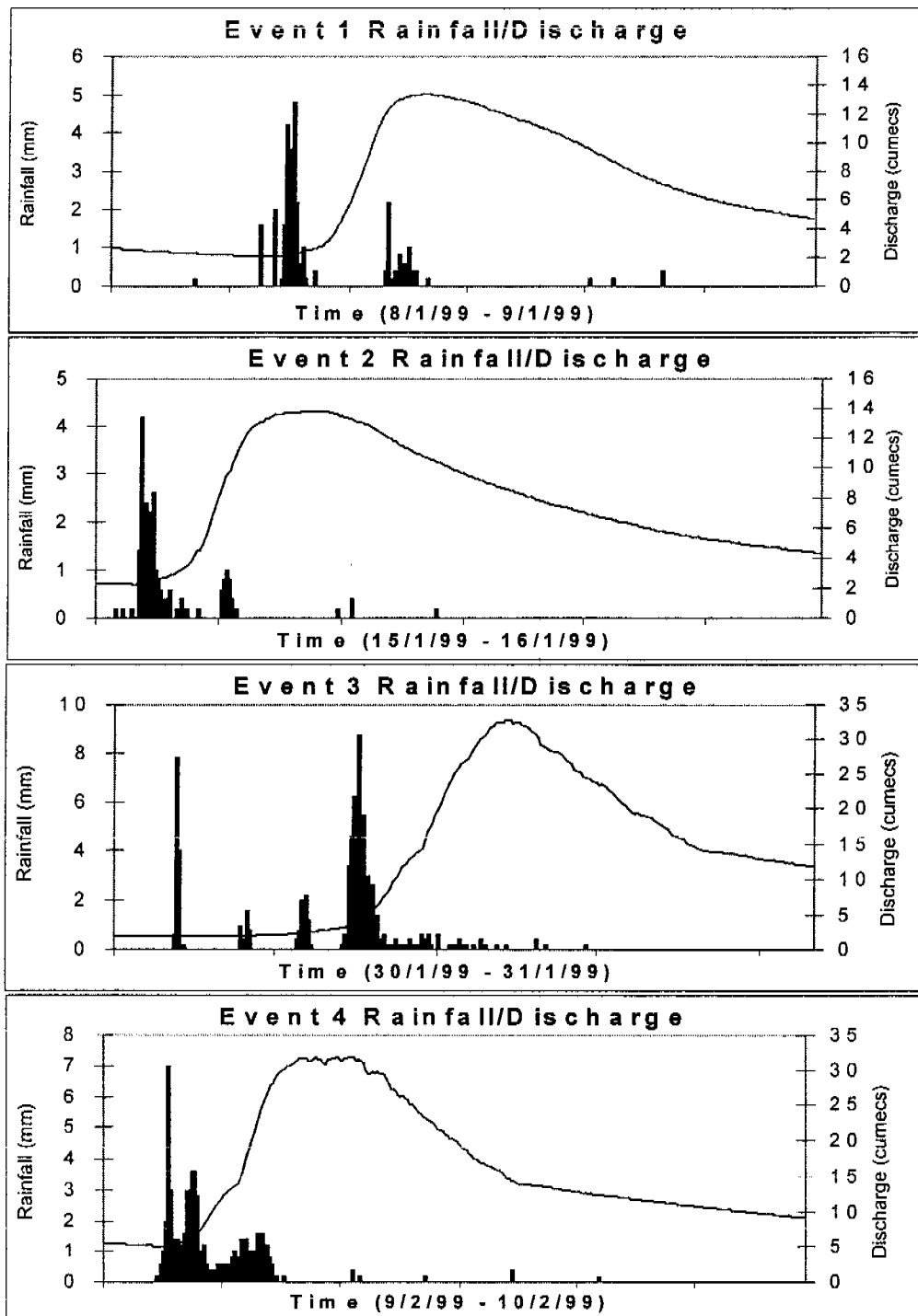


Figure B5: Rainfall/Discharge of selected events

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 hydrographs compared reasonably well with observed data for each event (Figure B6). 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 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 Swift Creek catchment at the downstream gauging was found to be slightly less than the observed values (Table B1), whilst the hydrographs were similar in shape.

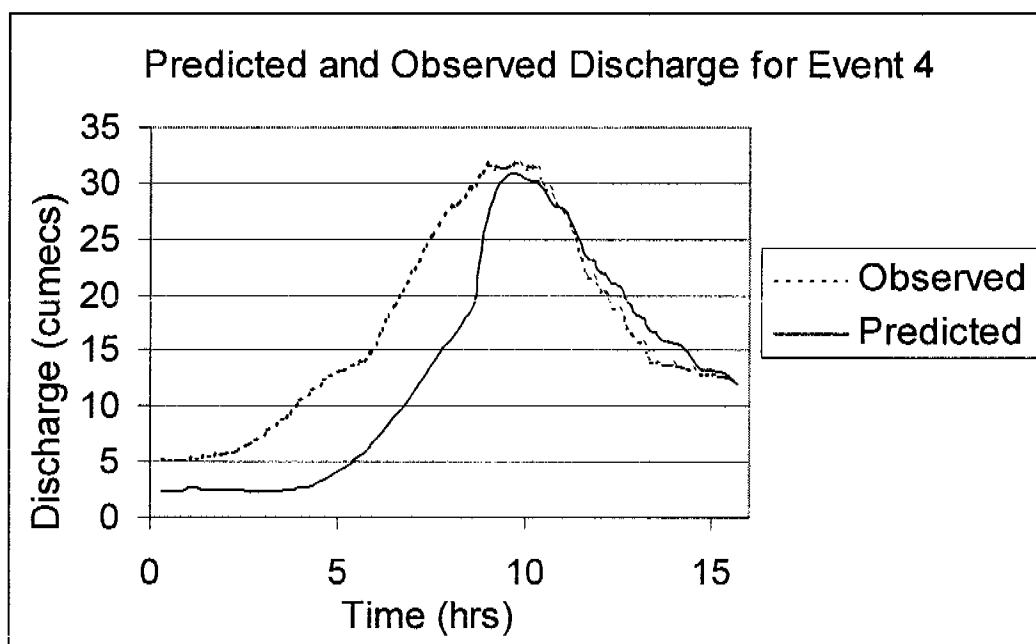


Figure B6: An example of a predicted hydrograph produced by DISTFW compared with the observed hydrograph.

Table B1 : The observed and predicted discharges for the 1998/1999 wet season in the Swift Creek catchment

| Observed Discharge (MI) | Predicted Discharge (MI) | Difference (%) |
|-------------------------|--------------------------|----------------|
| 33760.5 | 31575.8 | 6.5 |

B4.2 Sediment Transport Model

The sediment transport model (STM) to be used in this study is a standard equation used by geomorphologists and soil scientists relating discharge to total sediment loss. The STM has previously been used in the calibration of the SIBERIA landform evolution model (Evans et al., 1998; Willgoose and Riley, 1998). The sediment transport model used is of the form (Evans, 1997):

$$T = K \int Q^m dt \quad (B3)$$

where,

$$K = \beta_2 S^{n_1} \quad (B4)$$

where T = total sediment loss, $\int Q^m dt$ = cumulative runoff over the duration of the event (Q = discharge ($l s^{-1}$)), S = slope (m/m) and β_2 , n_1 and m_1 are fitted parameters. The parameters m_1 and K are fitted using multiple regression. However, although the correlation was high (correlation coefficient of 0.838), the equation tended to under-predict high sediment loss events. This is of particular concern as it is well recognised that large events generally dominate sediment loss. For example, 81 runoff producing rainfall events measured on the eastern Darling Downs of Queensland, six storms caused 70% of the total soil erosion (Wockner and Freebairn, 1991). At ERA Ranger mine 25% of storms monitored on site removed 54% to 73% of total sediment removed during all monitored events (Evans, 1997). As such, the final equation for predicting sediment loss in the Swift Creek catchment was found to be:

$$T = 0.08940353 \int Q^{0.871} dt \quad (B5)$$

It is important that large discharge events are not underpredicted as they are the most erosive. Ferguson (1986) considered that power curves of this form (Equation B5) underpredict sediment transport due to statistical bias. Therefore, a statistical bias correction factor, (1.119) has been incorporated in the coefficient of Equation B5.

B4.3 Scale analysis - Discharge area relationship

The parameters fitted here define how discharge used in the calculation of sediment transport rate varies with catchment area. The discharge-area relationship is described by Equation B2 (Willgoose and Riley, 1993).

Huang and Willgoose (1992, 1993) investigated the potential for using the DISTFW hydrology model to determine the relationship between discharge and area. Although this process has been used in previous SIBERIA studies (Willgoose and Riley, 1998; Evans et al., 1998), the methodology was deemed unsuitable for investigating the larger Swift Creek, as it assumes that the rainfall in all parts of the catchment are the same. The area dependence of discharge within Swift Creek was instead found using empirical peak discharge data from the field monitoring program (Figure B7). The relationship derived using these data is:

$$Q_p = 0.0004 A^{0.63} \quad (B6)$$

The acceptable range for m_3 values is 0.5 to 1.0 (Willgoose et al., 1991). The value determined here, 0.63, falls within that range.

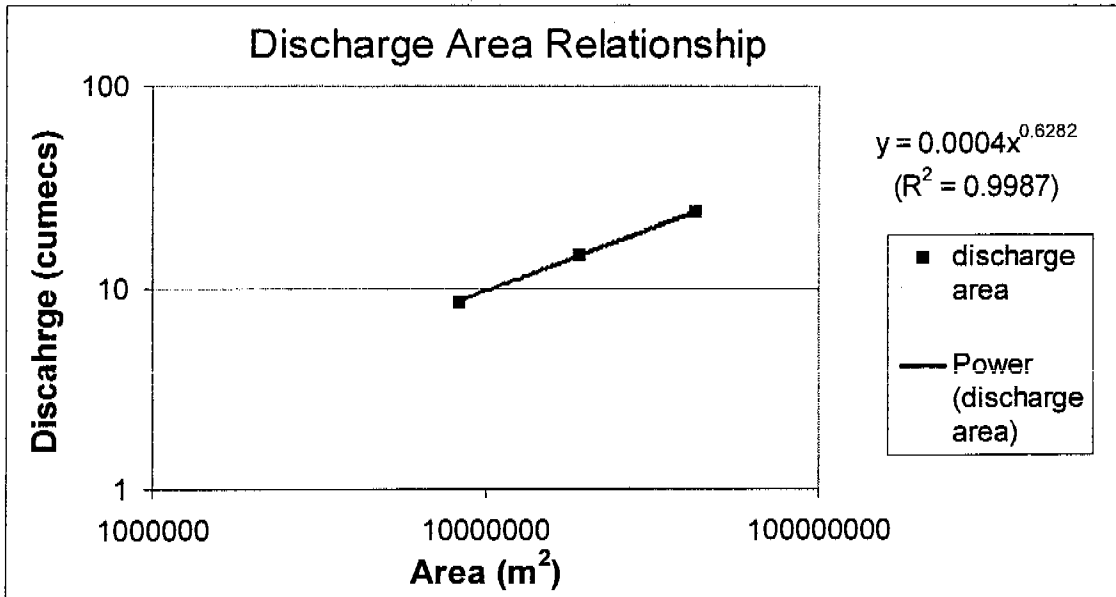


Figure B7: The peak discharge/area relationship exhibited by the field data

B4.4 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_s) in Equation (B1) for the Swift Creek catchment.

The steps were:

1. The fitted DISTFW model parameter values were used to generate long-term runoff for the Swift Creek 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 DTM node data.
2. The annual runoff determined in step 2 above was then used in the soil loss equation:

$$T = \beta S^{n_1} \int Q^{m_1} dt \quad (\text{B7})$$

where T = total sediment loss (g), $\int Q^{m_1} dt$ = cumulative runoff over the duration of the event ie. annual runoff (Q = discharge (L s^{-1})), S = slope (m/m) and β , n_1 and

m_1 are fitted parameters. Equation (B7) was used to determine an annual sediment loss (Mg y^{-1}) which was converted to a volume ($\text{m}^3 \text{y}^{-1}$) by dividing by the bulk density of the surface material (1.38 Mg m^{-3}) (Table B2). Using the annual sediment losses a long-term average sediment loss rate was then determined (q_s) for Equation (1) (Table B2).

3. The value of q_s was then used to determine β_1 by substituting Equation (2) into Equation (1) and transposing to give:

$$\beta_1 = \frac{q_s}{\beta_3^{m_1} A^{m_1 m_3} S^{n_1}} \quad (\text{B8})$$

where A is in m^2 . The value of n_1 was fixed at 0.69, as this value been derived in previous studies within the region (Evans et al., 1998)

Table B2: Long-term average soil loss, uncorrected for node scale, for the Swift Creek catchment

| Year | Rainfall (mm) | Soil Loss Mass Rate (Mg y^{-1}) | Soil Loss Volume Rate ($\text{m}^3 \text{y}^{-1}$) |
|--|---------------|--|--|
| 1972 | 1163 | 12413.2 | 8995.07 |
| 1973 | 1353 | 14161.2 | 10261.74 |
| 1974 | 1604 | 16464.5 | 11930.80 |
| 1975 | 1642 | 17028.3 | 12339.35 |
| 1977 | 928 | 10373.1 | 7516.74 |
| 1978 | 1467 | 16287.3 | 11802.39 |
| 1979 | 1193 | 13519.0 | 9796.38 |
| 1980 | 1663 | 17852.2 | 12936.38 |
| 1984 | 2082 | 21855.8 | 15837.54 |
| 1986 | 1145 | 12768.1 | 9252.25 |
| 1987 | 1277 | 13203.1 | 9567.46 |
| 1988 | 1135 | 12475.4 | 9040.14 |
| 1989 | 1152 | 12240.7 | 8870.07 |
| Average uncorrected soil loss volume rate (q_s) ($\text{m}^3 \text{y}^{-1}$) | | | 10626.64 |

B4.5 Slope correction

The q_s value (Equation B1) is implicitly derived for a value $S = 1$ m/m. Therefore β_1 (Equation B1) needs to be adjusted for use in SIBERIA. In SIBERIA simulations, A is in units of nodes 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 DTM. 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

$$\frac{1}{(DTM\ spacing)^n} = \frac{1}{50^n} \quad (B9)$$

The value β_1 parameter used in SIBERIA must include a multiplication by the correction factor derived in Equation (B8). Applying the correction factor to Equation (B7), a value of 42.28 was solved for β_1 . The values in Table B2 were derived assuming a slope, S , of 1.0m/m and therefore the q_s values are not real. The internal algorithm in SIBERIA corrects for true DTM node slope during simulations.

B5.0 GIS LINKAGE

B5.1 DISTFW Hydrology Model

Although the components of hydrological modelling predate GIS by more than a century, the two disciplines have converged strongly over the last 20 years. Hydrologic analysis has been integrated with computers to such an extent that computers often provide the primary source of information for decision-making by many hydrologic engineers (DeVantier and 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 and 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 two major objectives: 1) the development of a GIS toolbox that will allow the automatic generation of DISTFW input requirements and; 2) the development of a GIS interface from which the model can be launched. Objective 1 has been achieved, with objective 2 to be completed in the near future.

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 B3). 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 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 B3:

Table B3: 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 Tool | Calculates the flow relationships between sub-catchments. Directly determines 'maximum number of up slope sub-catchments' and 'sub-catchment incidence' for DISTFWs |
| Catchment Width Tool | Determines the average catchment width perpendicular to the central stream channel. Directly determines 'sub-catchment conveyance' values for DISTFW |
| Stream Length Tool | Computes the length of a catchment based on the central drainage channel. Directly determines 'the sub-catchment length' values for DISTFW |
| MinMaxArea Tool | 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 Tool | Reduces the area of a sub-catchment where one sub-catchment is downstream of another to the intervening area. |

It is proposed to link the DISTFW hydrology model with the GIS using a 'tight coupling' approach, as described by Fedra (1993). This level of integration will provide a common user interface for both the GIS and the model, with the file or information sharing between the respective components being transparent to the end user. The DISTFW hydrology model and the GIS will share the same database. There are various methods to implement this approach. This project will use higher-level

application language associated with the GIS in the creation of links between the GIS and DISTFW.

B5.2 SIBERIA Landform Evolution Model

SIBERIA models the evolution of a catchment through operations on cell-based (raster) digital elevation data 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 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 therefore requires the use of a relatively simple, loose coupling, which involves transferring data from one system to another through the storage of data on file and the subsequent reading of that file by the other (Fedra, 1993).

Although SIBERIA is based on relief, the data formats used by the model are significantly different to those used by GIS. There has been no direct methodology for allowing the two to easily exchange data. Research has been directed at developing GIS based tools that provide for the direct formation of SIBERIA inputs and processing of SIBERIA output data into a GIS readable format. Tools have now been developed to exchange elevation data between SIBERIA and the GIS. These help the user to prepare DEM based SIBERIA parameters within the GIS environment and analyse SIBERIA output using the spatial analysis capabilities of GIS. Further research is planned to allow the user to prepare the input requirements, launch the

model and extract the model output without leaving the GIS environment, thereby providing a relatively user-friendly front-end to this complex model.

B6.0 APPLICATION

The evolution of the Swift Creek catchment was modelled for a period of 500 years using the parameters derived in the previous sections. Figure B8 shows the areas of erosion and deposition predicted by SIBERIA. Figure B8 shows a clear differentiation in geomorphological activity between the less active floodplain areas and the more active upland plateau gorges boundaries of the Swift Creek catchment. No quantitative scale has been placed on the grey scale in Figure B8 because of the difficulty in assigning spatial changes in model parameters to the competent, very low erodible sandstone escarpment and uplands. The highest incision occurs at the large change of grade between the low gradient plateau and almost vertical escarpment also observed in simulation of the ERARM post-mining landform (Evans et al 1998, Willgoose and Riley 1998). Using one parameter value set applied to the whole DEM surface results in greatly over-predicting erosion and deposition in the vertical direction at the junction of the cliff face and plateau surface. The application of spatial variation of parameter values to account for the low erodible 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 Swift Creek catchment, on the other hand, shows widespread but low levels of deposition around the main creek channels and limited erosion on the interfluvial areas. However, an extensive backwater floodplain exists between the confluence of the Magela and Swift Creeks and the most downstream location covered by the Swift Creek DEM. It is expected that a large proportion of the

sediment moving from the Swift Creek catchment is deposited in this region. Future acquisition of digital elevation data for the backwater floodplain will allow investigation of these processes.

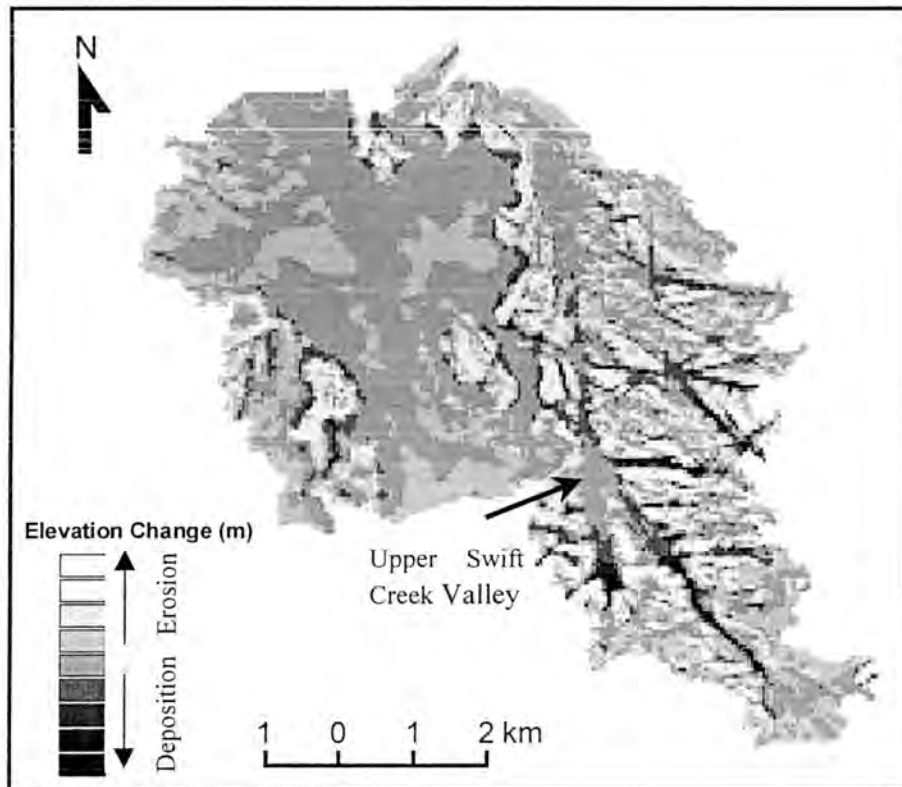


Figure B8: Differences in elevation, indicating areas of erosion and deposition, between the Swift Creek catchment at 0 years and after being modelled for a period of 500 years.

Although Figure B8 indicates that there is a high degree of spatial variation in erosion and deposition rates within the Swift Creek catchment, there is little variation in the general statistics associated with the catchment (Table B4). Over the 500 year period modelled, there was no change in the minimum and mean elevation and a relatively small drop in the maximum elevation. This indicates that the most active erosion occurs in the high escarpment areas, associated with steep changes in gradient as discussed above. At this stage, the simulated erosion rates in these areas appear to be

incorrect as a result of the non-spatial variation in parameter values. The high depositional areas in the upland gorges (qualitative only at this stage) and no variation in minimum elevations associated with the floodplain indicates that the Swift Creek catchment is a relatively closed system with much of the sediment eroded from the catchment being redeposited in temporary and permanent stores within the catchment. Further investigation is required to determine if this is associated with the preliminary nature of this study, or is a realistic indication of sedimentary processes in the Swift Creek catchment.

Table B4: General statistics for the Swift Creek catchment at 100 year intervals between 0 and 500 years.

| Year | Min | Max | Mean | STD |
|-------------|------------|------------|-------------|------------|
| 0 | 12.01 | 251.90 | 92.29 | 64.60 |
| 100 | 12.01 | 249.22 | 92.29 | 64.0121 |
| 200 | 12.01 | 246.95 | 92.29 | 63.50 |
| 300 | 12.01 | 244.79 | 92.29 | 63.05 |
| 400 | 12.01 | 243.99 | 92.29 | 62.64 |
| 500 | 12.01 | 243.27 | 92.29 | 62.26 |

This preliminary assessment of landform evolution in the Swift Creek catchment has applied one set of parameters to the entire Swift Creek catchment for the modelled period. This has been appropriate for small scale studies (Evans et al., 1998, Willgoose and Riley, 1998), however it is necessary that future research consider the spatial variability in parameters controlling landform evolution. This is especially important when applying GIS and landform evolution modelling techniques to assessing the impact of land management practises on catchment scale

geomorphological and hydrological processes. Linking SIBERIA to a GIS will facilitate a more spatially aware approach to assessing mining impact. The assessment of mining impact using the approach described in this study will also require consideration of the temporal evolution of landform evolution parameters. Moliere (2000) has described the progression of SIBERIA parameters over time associated with the rehabilitation of mine sites. This research will be incorporated into the assessment of possible future impacts of the ERAJM on the Swift Creek catchment.

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 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 alternatives obtained, various scenarios of mine site design will be modelled to assess possible impacts of the Jabiluka mine on landform evolution within the Swift Creek 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.

B7.0 CONCLUSIONS

The outcomes to date of this study provide a preliminary evaluation of integrated hydrology and landform evolution modelling techniques with GIS for assessing the possible impacts of mining on the Swift Creek catchment, Northern Territory. A database has been established that employs GIS as a framework for both spatial and attribute datasets associated with this project. This approach retains the flexibility and functionality required to store and manipulate each dataset independently, whilst offering a central hub for the various projects data. Hydrology and sediment transport parameters were derived from field data collected within the Swift Creek 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 Swift Creek 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.

● Additional research is required to develop a more fully integrated GIS and landform evolution modelling approach that is beneficial for the proactive management of mining and more wide ranging catchment management scenarios.

●

●

●

●

●

●

●

●

●

●

References

Arkinstal, M., Willgoose, G. R., Loch, R. J. and Pocknee, C. (1994). Calibration of DISTFW parameters for the QDPI rainfall simulator Oaky Creek. *Research Report No. 093.04.1994*, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, New South Wales, Australia.

Boggs, G. S., Evans, K. G., Devonport, C. C. and Saynor, M. (In Press). Developing a Geographic Information System for the Geomorphological Assessment and Management of Mining Impact. *Journal of Environmental Management*.

Boggs, G., Devonport, C., Evans, K., 1999. Total management of Swift Creek catchment using GIS. In NARGIS 99: proceedings of the 4th North Australian Remote Sensing and GIS Conference, Darwin, 28-30 June, 1999. Paper 15.

Bull, A., (1999). Past, present and future development of GIS at the Environmental Research Institute of the Supervising Scientist and the Office of the Supervising Scientist. Internal Report, Environmental Research Institute of the Supervising Scientist, Canberra. Unpublished paper.

Burrough, P., 1986. Principles of Geographical Information Systems for Land Resources Assessment. Oxford University Press, New York, p. 50.

Burrough, P. A. and McDonnell, R. A. (1998). *Principles of Geographic Information Systems*. Great Britain: Oxford University Press.

Charnock, T. W., Hedges P. D. and Elgy J. (1996). Linking multiple process level models with GIS, IAHS publication no. 235. In *Application of Geographic Information Systems in Hydrology and Water Resources Management* (K. Kovar and H. P. Nachtnebel, eds.), pp. 385 – 393. Wallingford: IAHS Press.

De Roo, A., 1996. Soil Erosion Assessment Using G.I.S. In: Singh, V.P., and Fiorentino M., (Eds.), *Geographical Information Systems in Hydrology*. Kluwer Academic Publishers, London, pp. 339 - 353.

Desmet, P. J. J. and Govers, G., (1995). GIS-based simulation of erosion and deposition patterns in an agricultural landscape: a comparison of model results with soil map information. *Catena*, **25**, 389 – 401.

De Vantier, B. A. and Feldman, A. D. (1993). Review of GIS Applications in Hydrologic Modeling. *Journal of Water Resources Planning and Management*, **119**, 2, 246 – 260.

Duggan, K., 1988. Mining and erosion in the Alligator Rivers Region of northern Australia. Ph.D. Thesis, School of Earth Sciences, Macquarie University.

Evans, K. G. (1997). *Runoff and erosion characteristics of a post-mining rehabilitated landform at Ranger Uranium Mine, Northern Territory, Australia and the implications for its Topographic Evolution*. PhD Thesis, University of Newcastle, NSW.

Evans, K. G. (2000). Methods for assessing mine site rehabilitation design for erosion impact. *Australian Journal of Soil Research*, **38**, 231-247.

Evans, K. G., Willgoose, G. R., Saynor, M. J. and House, T. (1998). Effect of vegetation and surface amelioration on simulated landform evolution of the post-mining landscape at ERA Ranger Mine, Northern Territory, *Supervising Scientist Report 134*, (Canberra: Supervising Scientist).

Fedra, K. (1993). GIS and Environmental Modeling. In *Environmental Modeling with GIS* (M. F. Goodchild, B. O. Parks, and Steyaert L. T., eds.), pp. 35 – 51. New York: Oxford University Press.

Ferguson, R. I. (1986). River Loads Underestimated by Rating Curves. *Water Resources Research*, **22**, 1, 74 – 76.

Field, W. G. and Williams, B. J. (1983). A generalised one-dimensional kinematic catchment model. *Journal of Hydrology*, **60**, 25-42.

Field, W. G. and Williams, B. J. (1987). A generalised kinematic catchment model. *Water Resources Research*, **23**, 8, 1693-1696.

Finnegan, L., 1993, Hydrolic characteristics of deep ripping under simulated rainfall at Ranger uranium mine, Internal Report 134, Supervising Scientist for the Alligator Rivers Region. Canberra, Unpublished paper.

Garbrecht, J., and Martz, L., 1994. Grid size dependency of parameters extracted from digital elevation models. *Computers and Geosciences*. 20, 1, 85 – 87.

Hill, J. M., Singh, V. P. and Aminian H. (1987). A computerized data base for flood prediction modeling. *Water Resources Bulletin*, 23, 1, 21 – 27.

Huang, H. Q. and Willgoose G. R. (1992). Numerical analyses of relations between basin hydrology, geomorphology and scale. *Research Report No 075.04.1992*, Department of Civil Engineering and Surveying, University of Newcastle, Australia.

Huang, H. Q. and Willgoose G. R. (1993). Flood frequency relationships dependent on catchment area: An investigation of causal relationships. *Towards the 21st Century, Hydrology and Water Resources Symposium, Newcastle, 1993*, The Institution of Engineers (Australia), pp. 287 – 92.

Hudson., N., 1973. Soil conservation, 2nd edn, BT Batsford Ltd, London.

Hutchinson, M., 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. *Journal of Hydrology* 106, 211-232.

Hutchinson, M., 1993. Development of a continent-wide DEM with applications to terrain and climate analysis. In: Goodchild, M.F., Parks, B.O., Steyaert, L.T., (Eds.), *Environmental Modeling with GIS*. Oxford University Press, New York, pp. 392-399.

Kinhill and Associates in association with Energy Resources Australia (1996). *The Jabiluka project: draft environmental impact statement*. Brisbane.

Lane, L., Renard, K., Foster, G., Laflen, J., 1992. Development and Application of Modern Soil Erosion Prediction Technology - The USDA Experience. *Australian Journal of Soil Research*, 30, 893 - 912.

Leopold, L. B., Wolman, M. G. and Miller, J. P. (1964). *Fluvial processes in geomorphology*. London: Freeman.

Maidment, D. R. (1996). Environmental modeling within GIS. In *GIS and Environmental Modeling: Progress and Research Issues* (M. F. Goodchild, L. T. Steyaert, B. O. Parks, C. Johnston, D. R. Maidment, M. Crane and S. Glendinning, eds.), pp.315 – 323. New York: Oxford University Press.

Mitas, L., Mitasova, H., 1998. Distributed soil erosion simulation for effective erosion prevention. *Water Resources Research*, 34 (3), 505 – 516.

Mitchell, J., Bubenzer, G., 1980. Soil loss estimation. In: Kirkby, M.J., Morgan, R.P., (Eds.), *Soil Erosion*. Wiley, Brisbane.

Moliere DR. 2000. Temporal Variation in Erosion and Hydrology Parameters on a Rehabilitated Mine Site. Masters Thesis. *University of Newcastle*.

Moore, I. D., Grayson, R. B. and Ladson, A. R. (1991). Digital terrain modeling: A review of hydrological, geomorphological and biological applications. *Hydrological Processes*, 5, 3 – 30.

Pilesjö, P., 1992. GIS and Remote Sensing for Soil Erosion Studies in Semi-arid Environments – Estimation of Soil Erosion Parameters at Different Scales. Lund University Press, Sweden.

Pilotti, M., Bacchi, B., 1997. Distributed evaluation of the contribution of soil erosion to the sediment yield from a watershed. *Earth Surface Processes and Landforms*, 22, 1239–1251.

Puig P., Devonport C. and Evans K., 2000. Rapid Assessment of Erosion Risk in 7J Creek Catchment using GIS. Internal Report. Supervising Scientist, Canberra. Unpublished paper.

Quinn, P. F., Bevan, K., Chevallier, P. and Planchon, O. (1992). The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. In *Terrain Analysis and Distributed Modelling in Hydrology* (K. J. Beven and I. D. Moore, eds.) pp. 63 – 83. New York: John Wiley & Sons.

Raper, J. and Livingstone, D. (1996). High-Level Coupling of GIS and Environmental Process Modeling. In *GIS and Environmental Modeling: Progress and Research Issues* (M. F. Goodchild, L. T. Steyaert, B. O. Parks, C. Johnston, D. R. Maidment, M. Crane and S. Glendinning, eds.), pp. 387 – 390. New York: Oxford University Press.

Renard, K., Laflen, J., Foster, G., McCool, D., 1994. The Revised Universal Soil Loss Equation. In: Lal, R., (Ed.), Soil Erosion Research Methods, Second Edition. Soil and Water Conservation Society, Alkeny, pp. 105-124.

Rieger, W. (1998). A phenomenon-based approach to upslope contributing area and depressions in DEMs. *Hydrological Processes*, **12**, 857 – 872.

Schultz, G. A. (1993). Application of GIS and remote sensing in hydrology. In *HydroGIS 93: Application of Geographic Information Systems in Hydrology and Water Resources*, IAHS Publ. no. 211 (K. Kovar and H. P. Nachtnebel, eds), pp. 127-140. Wallingford: IAHS Press.

Singh, V. P. and Fiorentino, M. (1996). Hydrologic modeling with GIS. In *Geographical Information Systems in Hydrology* (V. P. Singh and M. Fiorentino, eds.), pp. 1 – 13. London: Kluwer Academic Publishers.

Steyaert, L. T. (1993). A Perspective on the State of Environmental Simulation Modeling. In *Environmental Modeling with GIS* (M. F. Goodchild, B. O. Parks and L. T. Steyaert, eds.) pp. 16 – 30. New York: Oxford University Press.

Walling, D., 1983. The sediment delivery problem. *Journal of Hydrology* **65**, 209–237.

Walling, D., 1984. Sediment delivery from drainage basins. In: Loughran, R.J., (Ed.), Drainage Basin Erosion and Sedimentation. Conference Papers, University of Newcastle and Soil Conservation Service of NSW, Newcastle, pp. 71–80.

Wharton, G., 1994. Progress in the use of drainage network indices for rainfall-runoff modelling and runoff prediction. *Progress in Physical Geography* 18, 539–557.

Willgoose, G. and Riley, S. (1993). Application of a catchment evolution model to the prediction of long-term erosion on the spoil heap at the Ranger uranium mine: Stage I report, *Open file record 107, Supervising Scientist for the Alligator Rivers Region, Canberra*. Unpublished paper.

Willgoose, G. R. and Riley, S. R. (1998). Application of a catchment evolution model to the prediction of long-term erosion on the spoil heap at Ranger uranium mine: Initial analysis, *Supervising Scientist Report 132*, (Canberra: Supervising Scientist).

Willgoose, G. R., Bras, R. L. and Rodriguez-Iturbe, I. (1989). *A physically based channel network and catchment evolution model, TR322.*, Ralph M. Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Willgoose, G. R., Bras, R. L. and Rodriguez-Iturbe, I. (1991). Results from a new model of river basin evolution. *Earth Surface Processes and Landforms*, 16, 237-254.

Willgoose, G. R., Kuczera, G. A. and Williams, B. J. (1995). 'DISTFW-NLFIT: rainfall-runoff and erosion model calibration and model uncertainty assessment suite user manual', *Research Report No. 108.03.1995*. The University of Newcastle, Department of Civil, Surveying and Environmental Engineering.

Wischmeier, W., Smith, D., 1958. Rainfall energy and its relationship to soil loss. Transactions of the American Geophysical Union 39, 285–291.

Wischmeier, W., Smith, D., 1978. Predicting rainfall erosion losses - A guide to conservation planning. US Department of Agriculture, Agriculture Handbook No. 537, US Government Printing Office, Washington DC.

Wockner, G. W. and Freebairn, D. M. (1991). Water balance and erosion study on the eastern Darling Downs -- An update. *Australian Journal of Soil and Water Conservation*, 4, 41-47.