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Rapid assessment of erosion risk in 7J Creek catchment using GIS

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supervising scientist

RAPID ASSESSMENT OF EROSION RISK IN 7J CREEK CATCHMENT USING GIS

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1. INTRODUCTION

1.1 Overview

A literature review of applications of GIS to rapid assessment of erosion leads to the selection of the Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1978) as most suitable model for the development of a prototype GIS based rapid assessment of erosion risk model in the Alligator Rivers Region (ARR) of the Northern Territory of Australia.

The adapted prototype model reduces the USLE to the product of three main factors - soil erosivity (K), slope (S) and cover (C). Initial values of K, S and C are estimated for land units of the Magela Creek in the ARR. A GIS of 7J Creek (a subcatchment of the Magela Creek) based on a DEM and a digital map of land units provides an assessment of the potential of this approach. The results are discussed and a strategy is proposed for the implementation of the model.

The encouraging outcome of this feasibility study indicates that GIS can help to rapidly identify high erosion risk areas within a catchment using existing data sets in the Northern Territory of Australia.

1.2 Background

The Environmental Research Institute of the Supervising Scientist (***eriss***) carries out independent research into the environmental effects of uranium mining. The Erosion and Hydrology (E&H) program at ***eriss*** is concerned, *inter alia*, with gauging the impact of mining on catchment geomorphologic processes and landform evolution as a significant factor in the environmental impact assessment of mining in mineral leases adjacent to the world heritage Kakadu National Park (KNP). This assessment requires extensive in depth research, monitoring and collection of field data, and sophisticated modelling techniques over a period of years. Before these procedures are put in place, it is necessary for management to quickly acquire existing data and evaluate it to assist in planning of the detailed monitoring and modeling programs. The initial development of a rapid assessment technique for the purpose of assessing one aspect of landform evolution, namely erosion, is the subject of this report.

Erosion is the combined effect of a number of significant factors that play a role in the evolution of landforms. 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. It is also important to identify areas of risk at the start of a monitoring program so that different risk categories are monitored appropriately. Assessment of erosion has been a topic of interest to humankind for thousands of years and there is a large body of knowledge about the process. The region of interest in the wet-dry tropics to E&H contains both natural and disturbed environments. A literature review was undertaken to provide information relevant to the formulation of this project and this is discussed later in the report and expanded on in an appendix.

A geographic information system (GIS) was used in this project to satisfy the requirement for storage and analysis of spatial data. This approach was facilitated by the fact that ***eriss*** already had a geographic information system in place populated with data suitable for initial studies. This data consisted of baseline Australian Land Information Group (AUSLIG) elevation and drainage layers (detailed later) as well as land units data digitised and collated during past projects in the Magela Creek catchment (Devonport 1992, 1993; Bull 1999).

7J Creek catchment was selected because it is a small, typical sub-catchment of the Magela Creek catchment. The Magela Creek catchment contains the ERA Ranger and Jabiluka mines and there are erosion data available from previous work (Wells 1979, Duggan 1991). It is intended that the approach outlined in this report be tested and further extended in a more critical adjacent catchment where mining is likely to take place in the near future.

The significance of this study is that it takes the first steps towards the development of a GIS-based model for rapid assessment of erosion risk in a small catchment using existing and available data sources in the wet-dry tropics of northern Australia. The potential demonstrated through the conceptual development in this report will be very useful to ***eriss*** and other organisations interested in impacts on the environment in northern Australia.

This report is part of the outcome of a GIS research project undertaken by Phillipe Puig as part of a Graduate Diploma in Geographic Information at Northern Territory University (NTU) in Darwin. The project topic was framed by Ken Evans from ***eriss*** in Jabiru and supervised by Chris Devonport from NTU.

1.3 Report outline

The section "Application of GIS and erosion assessment/prediction", reviews studies of erosion and GIS implementation relevant to the wet-dry tropics of the Northern Territory. The USLE is selected as the most suitable model for rapid assessment of erosion risk. The variables in this equation are explored and initial simplifications of the original expression are considered along with a conceptual methodology for the acquisition of field data.

"Initial model factor estimations", outlines how the parameters K, S and C were estimated from available data and published charts for the purpose of this concept feasibility study. The rationale behind this approach is analysed and its limitations emphasized.

"7J catchment prototype GIS", offers an example of practical implementation of the modelling strategy in 7J creek, a small catchment of the Alligator Rivers Region of Arnhem Land in the Northern Territory. The Spatial Analyst extension of ArcView GIS is used to derive the geometry of the catchment from a DEM. A map of land units of the corresponding area provides information from which values are derived for K, S and C. Finally the GIS model generates a map of erosion risk in the 7J creek catchment. A simple mathematical method of accounting for the respective importance of the USLE parameters in a specific environment is proposed.

To conclude we consider some inherent limitations of the USLE, their implications and the research required to overcome these hurdles. Hardware and software desirable for the implementation of the method outlined are briefly reviewed with the predicted future of this strategy.

1.4 Definitions and Acronyms

ARR	Alligator Rivers Region
DEM	Digital Elevation Model
dGPS	differential Global Positioning System

ERI	erosion risk index
eriss	Environmental Research Institute of the Supervising Scientist
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GPS	Global Positioning System
IT	Information Technology
KNP	Kakadu National Park
NT	Northern Territory
RS	Remote Sensing
E&H	Erosion and Hydrology program (***eriss***)
SAR	Synthetic Aperture Radar
SSG	Supervising Scientist Group
USLE	Universal Soil Loss Equation

2. GIS AND EROSION ASSESSMENT/PREDICTION

2.1 Regional studies

Wells (1979) documents land resource mapping, erosion and soil erodibility studies conducted by the Territory Parks and Wildlife Commission of the NT during the dry season of 1978 in the Ranger, Jabiru and Jabiluka area. Soil erodibility in the Magela catchment is rated as slight to moderate due to the rapid to very rapid infiltration rate in undisturbed soil situations. This in turn minimises run off. During the 1978 dry season the most significant areas of erosion were in Jabiluka where, compared with the Ranger site, the soil is essentially gravel free. The different terrains and corresponding land systems in that area include plateau surface, rugged terrain (plateau side slopes), undulating upland terrain, alluvial plains on freshwater sediments, alluvial clay plains and swamps, and littoral areas.

Duggan (1991) assessed the erosion and geomorphic stability of eight catchments in the vicinity of Ranger, Nabarlek, Koongarra and Jabiluka mine leases. Four catchments were in areas of no mining (Koongarra creek, 7J creek that flows across Jabiluka mine lease, and Georgetown and Gulungul creeks near the Ranger lease). Her objectives included the monitoring of selected streams and establishment of flow parameters that were used to establish flow-sediment discharge relationships to gain a better understanding of erosion in the area. Her study involved direct measurement of erosion on slopes using erosion plots and pins as well as measurements of sediment yields. She identified several factors affecting erosion in the natural lowlands including burning (erosion higher on burnt sites), gravel lag (gravel deflects linear flow thus minimising rilling), litter cover (minimises erosion). On the natural lowlands there was no apparent correlation between slope and erosion or between vegetation and erosion. On lowland slopes, litter and gravel armour, also appeared to be the main factors controlling erosion. The washloads recorded in the four natural catchments vary between 4 and 66 t/km^2/year depending on catchment and yearly rainfall. The erosion in the Koongarra catchment was nearly three times greater than in the 7J creek catchment.

More recent research has address the application of 3-dimensional landform evolution modeling to mine site rehabilitation design (Evans et al. 1998, Willgoose and Riley 1998). Technology is now at a stage where incision rates of containment structures can be quantified. This can be used in the design of containment structures encapsulating contaminants. Evans et al (1991) define two categories of useful erosion prediction models:

- USLE, WEPP, GUESS, CREAMS are soil loss prediction models on short or long term basis
- TOPOG, SIBERIA, ANSWERS that are 3-dimensional models.

2.2 Erosion models

The USLE, developed for the United States Department of Agriculture is probably the most widely used and well known of the soil loss prediction models. The USLE is based on half a century of erosion research in the USA and models soil losses from sheet and rill erosion primarily for agricultural sites but can be extrapolated to non-agricultural environments. This model does not compute sediment yields from gully, streambank and streambed erosion. It predicts soil loss due to erosion for combinations of crop system and management practice, soil type, rainfall pattern, and topography. This equation (see section 3.1) groups the many interrelated erosion processes into six factors: rainfall and runoff (R), soil erodibility (K), topographic (LS) combining a slope-effect (S) and a slope-length effect (L), cover management (C), and support practice (P).

This model has been used extensively with GIS applications including for example

(i) Flacke et al. (1990) who used the USLE in conjunction with a DTM to map soil loss due to erosion;

(ii) Xongchao (1988) who mapped water erosion risk with ARC/INFO using the USLE; and

(iii) Landassess Decision Support System (DSS) described by Bischof (1996). The Landassess DSS was designed to evaluate sustainability of grazing management based on a modelling approach which characterised the landscape on the basis of the concept of land unit and an assessment of soil erosion risk based on an adaptation of the USLE and an assessment (on a five class scale) of the type of soil erosion process a particular land unit would be susceptible to. These assessments took into account landform characteristics (slope, position), organic matter content, texture, and vegetation.

Many other approaches have been put forward where models have been coupled with GIS. These include, for example, the estimation of surface runoff and erosion (De Roo 1991), the estimation of sediment budgets (Milne et al. 1997), the calculation of indices (slope curvature, index of saturation potential, index of landform, fetch and directional relief indices) to quantify the characteristics of a landscape (Walsh et al. 1998), modeling of erosion and sediment yield (Meijerink et al.1986; Moussa 1991), and the assessment of erosion risk/hazard (Jong & Riezebos 1992; McCabe 1997). There are, it would seem, as many approaches as there are projects which implies that there is much variability in the factors affecting erosion in different regions and at different sites.

2.3 Remote sensing

Many scientists have used remotely sensed images to assist in their soil erosion prediction projects. In general this approach has been successful when applied to broad scale areas. For example, Pickup and Chewings (1990) mapped and predicted soil erosion patterns using Landsat images in central Australia. They described broad scale conceptual and mathematical models of soil erosion on flat arid lands and produced a translation of standard Landsat MSS data into soil stability index. Other authors have used remotely sensed data to assist in the assessment and monitoring of various factors such as slope, soil type, vegetation cover (e.g. Singh 1991; Fitzpatrick 1993; Hinton 1996). The historical absence of successful projects on small catchments is probably related to the relatively course resolution of remotely sensed data that has been available in the past. New technologies may well provide the potential to reassess the usefulness of remotely sensed data for smaller areas.

2.4 Evaluation

As a result of this literature review the following generalisations relevant to the development of a rapid assessment technique can be summarised:

- There is no ready made technological solution to rapid assessment of erosion in the wet-dry tropics,
- Of the available erosion models, the USLE has good potential for adaptation to local environments,

- The USLE has been used extensively with GIS by previous researchers which suggests that technical implementation is feasible with limited resources,
- Alternative models, especially topographic evolution models, are complex and require data often not readily available for calibration, and
- An index of erosion risk is a more achievable objective for rapid assessment than quantitative predictions.

3. Rapid Assessment Model Development

3.1 USLE

The variables in the USLE are (Wischmeier & Smith 1978):

$$A = R \cdot K \cdot S \cdot L \cdot C \cdot P$$

- A is the computed soil loss per unit area
- R, the rainfall and runoff factor, or erosivity index, is derived from the greatest average intensity recorded in 30 minute periods during storms
- K, the soil erodibility factor, reflects the sensitivity of a soil to erosion under specific conditions ("...measured on a unit plot, which is defined as a 22.6m length of uniform 9% slope continuously in clean tilled fallow").
- L, the slope length factor, or length factor, is the ratio of soil loss from the slope length considered to that from a comparable 22.6m length.
- S, the slope-steepness factor, known as slope factor, is the ratio of soil loss observed to that from a comparable 9% slope.
- C, the cover and management factor, or crop management factor, is the ratio of soil loss from an area with a specified cover to that from an identical area in tilled continuous fallow.
- P, the support practice, or conservation practice factor, is the ratio of soil loss observed to that with straight-row farming up and down the slope.

The USLE was developed to quantify the influence of different cropping practices on erosion. Practically this equation relies on ratios (L, S, C, P) between measurements from standard unit plots to those from similar agricultural plots. At first sight this model is poorly suited to an estimation of erosion in natural environments (Hudson 1976, 190). The original equation is unlikely to predict soil loss from small natural catchments because only properties influencing erosion of arable land are considered, deposition is not built into the equation, and gully and stream bank erosion are ignored. However, the USLE provides a logical framework to explore available information while refining initial data. This versatility makes the USLE well suited to developing countries where resources and historical data are scarce (Hudson 1973, 191-194).

3.2 Significance of model factors

The equation can be simplified to $A = K \cdot S \cdot C$ if the remaining parameters can be assumed to remain constant in the area under investigation. This approach at least allows a relative assessment between sites. These general characteristics of the USLE provide a useful initial model that has the potential to evolve as the understanding of the environment considered becomes more sophisticated.

In this concept feasibility study, R, L and P are not included in the initial model for the following reasons:

R, the rainfall erosivity index, reflects the energy content of the rain. It appears that in the Alligator Rivers Region (ARR), the rainfall itself is an acceptable surrogate (Cook G, pers. comm.). Regardless of the actual value of R this variable remains constant in what we may call a "rainfall land unit". We can assume, as a first approximation, that in a small catchment such as 7J

Creek, R is constant. R can therefore be ignored, as it will not be responsible for any variation in erosion within that "rainfall land unit".

L, the slope length factor, is not suited to natural environments (without fields) and any surrogate calculation is simply an estimation. S and L are often considered together and this is discussed further below;

P, the support practice, in a natural environment is equal to 1. P can therefore be removed from the equation.

K, the soil erodibility factor, C, the cover factor, and S, the slope factor were consequently determined to be the essential factors required for the initial model.

In practice, K can be obtained through field measurements and laboratory analysis (Loch and Rosewell, 1992; Evans and Loch, 1996). Canopy cover, surface vegetation and gravel lag combine to influence C. The canopy cover can be estimated with a spherical mirror used to visualise the respective proportions of canopy and sky. Surface cover can be determined using quadrants. The environment (tree association, geomorphology, patchiness, etc.) where the field data are collected, should be carefully described in terms of possible surrogates which would allow the estimation of these variables from remotely sensed images. Warner & Wasson (1992) suggest that dominant plant communities would be appropriate surrogates.

A review of existing data revealed that estimated values of K, S and C could be derived, in the first instance, from the land unit descriptions of Wells (1978), the AUSLIG 9 second DEM, and a more detailed DEM commissioned earlier by ***eriss***.

A study site, 7J Creek catchment, in the ARR was selected for the purpose of demonstrating and evaluating the concepts outlined above through the development of a prototype GIS for rapid assessment of erosion risk.

4. INITIAL MODEL FACTOR ESTIMATIONS

4.1 Estimation of K

The dominant soils in the attributes of the land unit data are summarised in Table 1. They vary substantially across the catchment that includes sandstone escarpment, floodplain and lowland topography.

The soil erodibility factor (K) was initially estimated from soil texture and percentage organic matter using data from Mitchell & Bubenzer 1980. This information is presented in Table 2 and is used as input to Table 1 which illustrates some characteristics of relevant soil properties of land units and contains four fields:

- Land Unit code
- Dominant Soil Type (Wells, 1979)
- %OM (percentage of organic matter in the soil), and
- K (erodibility index)

Table 1: Soil properties of the land units of 7J Creek

Land Unit	Dominant Soil Type	% OM	K
1a	Shallow lithosols	<0.5%	0.05
2a	Shallow lithosols	<0.5%	0.05
3c2	Shallow gravelly red massive earths	2%	0.24
4a	Moderately deep gravelly yellow massive earths	2%	0.3
4b1	Shallow gravelly yellow massive earths	4%	0.33
4b2	Shallow gravelly yellow massive earths	4%	0.33
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
7a1	Black cracking clay	4%	0.29

The K values in Table 1 estimated from Table 2 and the description of the land unit soils, although not confirmed by field data, constitute an acceptable starting point for this concept feasibility study. The reasoning used is demonstrated for a lithosol in Table 1. A lithosol in Table 1 would contain essentially quartz sand eroded, transported and deposited from the Kombolgie sandstone of the Arnhem Land Plateau. This lithosol being nearly pure quartz would be characterised by %OM<0.5. Having a sand texture this lithosol would therefore be assigned a K value of 0.05 according to Table 2. Land Unit 1a in Table 1 has therefore an estimated K value of 0.05.

Table 2: Soil erodibility factor K estimated from soil texture and percentage organic matter (from Mitchell & Bubenzer 1980).

Texture Class	Organic <0.5% K	Matter 2% K	Content 4% K
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

4.2 Estimation of Slope

The slope factor S_n in the table below does not follow the definition of the slope factor S in the USLE.

When the components of the USLE are reviewed, S, the slope-steepness factor, is described as the ratio of soil loss observed to that from a comparable 9% slope. To be consistent with the approach adopted earlier, as there are no data available for the soil loss from a 9% slope, the initial slope steepness factor will be assigned the normalised slope. This simplification is preferable to the angular measurement of the slope for at least two reasons:

the normalised slope is a ratio which is consistent with the initial definition of S, and

small variations in slope within a given range are better represented

S_n is a normalised slope factor that, in this initial construction of the model, is evaluated within a single catchment. The geographically restricted nature of this slope factor is required in order to consider, as explained previously, that R can be assumed to be constant and therefore ignored. Normalisation, although not necessary, eliminates the need to specify units which is consistant with the purpose of ultimately deriving a risk index.

Table 3: Slope and normalised slope index S_n in relevant land units for 7J catchment

Land Unit	Slope (degrees)	S_n (0-10)
1a	<10	7
2a	+/-40	10
3c2	<1	.5
4a	<2	1.5
4b1	<3	3.5
4b2	<4	2.5
5a	<2	3.5
5b	<2-3	1.5
5d	<4-10	7
5e	<2	1.5
7a1	0 (Flat)	0

4.3 Estimation of Cover

Researchers have found that C is of prime interest and is a key component in the model. This factor accounts for the protection given by canopy cover, gravel lag and ground cover against erosion.

The characteristics of the land units are listed in Table 5 and a cover index CI is derived by subjectively (in absence of field measurements) comparing the assumed protection against erosion offered either by canopy or gravel lag in different environments. The additional description of land units in Table 4 was used to augment the knowledge base for the estimate C_n in Table 5. The normalised cover index used here is called C_n to avoid confusion with the true USLE C and to be consistent with the symbol used previously for the slope factor. Values of C can, in theory, be derived from the literature but no suitable data were identified for the Magela Creek area when this report was prepared. C is likely to be dependent on local factors such as type of vegetation and the presence of gravel lag.

Table 4: Description of the land units of 7J Creek.

Land Unit	Terrain Category	Other Characteristics
1a	Plateau surface	Extensive rock and stone cover
2a	Plateau Side Slopes	Includes scarps and cliff faces
3c1	Undulating Upland	Upper wash slope areas
3c2	Undulating Upland	Lower wash slope areas, less well drained than 3c1
4a	Undulating Upland	Open forest on gentle colluvial slopes
4b1	Undulating Upland	Woodland to low open woodland
4b2	Undulating Upland	Dense scrub
5a	Low Lying Drainage Slopes	Generally associated with upland terrain
5b	Low Lying Drainage Slopes	Lower wash slopes commonly beneath 5a
5d	Low Lying Drainage Slopes	Colluvial slopes adjacent to sandstone plateau outlier
5e	Low Lying Drainage Slopes	Drainage line areas
7a1	Alluvial Clay Plains	Grassland with emergent Melaleuca, poorly drained

Table 5: Estimation of C_n

Unit	Soil cover	Vegetation	CI	C_n
1a	Abundant quartz sandstone	Scattered scrub	2	5
2a	Frequently stony/gravely	Grassland to low open woodland	2	5
3c2	50 to 80% surface gravel	Woodland to open forest	1	4
4a	Coarse quartz sand, 5 to 10% gravel	Open forest	3	6.7
4b1	Up to 60% surface gravel	Woodland to low open woodland	2	5
4b2	Up to 30% surface gravel	Dense scrub	2	5
5a	Some coarse quartz sand veneer	Woodland to low open woodland	3	6.7
5b	Moderately deep siliceous sands	Woodland with grassland	3	6.7
5d	Moderately deep siliceous sands	Variable tall open wood to scrubland	3	6.7
5e	Alluvial soils or sands	Grassland with areas of woodland	4	10
7a1	Hard set black soil, often gilgaid	Grassland with Melaleuca	4	10

Table 5 above ranks the different units from the least (4) to the best (1) on the basis of the protection they would offer a soil against erosion. The normalised cover index C_n renders the process of estimation of CI irrelevant in the context of this study as by normalisation on a scale of 10, values of C_n will always be without unit and in the range of 1 to 10.

4.4 Problems with this approach

Simplicity and time constraints resulted in only the DEM and the digital map of land units being used as inputs to this study. Aerial photographs and satellite images could be useful although conventional groundtruthing techniques would obviously not be possible with historical data. In the context of this feasibility study, the current accuracy of the digital map of land units, which was published in 1978 from earlier studies, has been accepted although for the purpose of groundtruthing, this map may be unsuitable since bushfires and annual floods since the date of acquisition have probably altered the vegetation cover and consequently the protection canopies provide against rain splash. During tropical storms, strong winds impart a high kinetic energy to raindrops which dislodge soil particles on the ground surface, mobilise them and consequently initialise the process of erosion. The resulting impact of canopy alteration and particularly gravel lag removal on erosion in this area is considerable. According to Duggan (1991), ground cover is one of the most significant controls of erosion in this area.

A description of soils more detailed than the land unit classification offers (see Table 1) would be preferable. While the K values estimated from the soils and land cover description of the land units are acceptable in the framework of a concept feasibility study, quantitative soil properties would be required to actually apply this equation.

Geomorphologic mapping from remotely sensed images is already possible but the rapid development of SAR means that there will almost certainly be, in the foreseeable future, remote sensing methods for accurately identifying (after groundtruthing) soil surface properties. With refinements in the classification of SAR images, the susceptibility of RADAR reflected signals to soil properties would provide a more reliable means of assessing K without undertaking an expensive soil survey.

The map of land units is not an ideal source of information for the estimation of slope and erodibility as land units are useful in ecology but of less use for engineering purposes. The main criticism of land units, in this context, is that they carry information so vague that they are difficult to adapt. Unit 4b1 (see Table5), for example, contains up to 60% surface gravel. This type of information is difficult to use in the context of erosion studies as it suggests that the abundance of surface gravel varies considerably thus making it impossible to derive a unique measure of cover.

The classification of the Magela Creek catchment into 15 land units based on vegetation, landform and a soil description is not ideal for this investigation as Warner & Wasson (1992) consider that the correlation between landform units and vegetation communities, in the Magela Creek basin, is weak. The correlation between topographic units and dominant plant communities was much stronger. They advocated a geomorphic classification that would lead to a map of surface layer expressed in terms of grain size, clay and organic matter content. A classification of terrains based on geomorphology, were it available, would probably give a map more suitable to the input requirements of the USLE model. However, geomorphological mapping is obviously not an appropriate component of rapid assessment.

5. 7J CREEK CATCHMENT PROTOTYPE GIS

5.1 Resources

NTU staff have a long-standing relationship with ***eriss*** that dates back over ten years of collaborative work in the Alligator Rivers Region (for example, Devonport and Waggitt 1994; Devonport and Bull 1999) including work on earlier prototype GIS systems associated with minesite rehabilitation and risk/hazard assessment (for example, Devonport 1992, 1993). It was decided to build on this previous work to facilitate a short term, quick response to the current issues while at the same time enabling the development of in-house knowledge and skills in the GIS domain. ARRGIS, a GIS set up for the Alligator Rivers Region by Devonport (1992), is the source of the land units coverage derived from documents compiled by the Land Conservation Unit of the Territory Parks and Wildlife Commission in 1978.

5.2 The Study Site

The 7J catchment was selected as a suitable study site (Figs. 1 & 2) for this project as it is a small catchment in the same region as Swift Creek (the site of the proposed Jabiluka uranium mine), and previous work has been conducted in the catchment by Wells (1978) and Duggan (1991). The catchment, a major right-bank tributary of Magela Creek, lies partly in ERA mineral leases and partly in the World Heritage listed area of Kakadu National Park. The dominant geology is the Holocene alluvium (floodplains), Early Proterozoic Cahill Formation (lowlands) and Pre-Cambrian Koombolgie Sandstone (Arnhem Plateau). The area receives high-intensity storms and rain depressions between October and April (wet season) with little rain falling during the remainder of the year (dry season). The average annual rainfall is 1 480 mm.

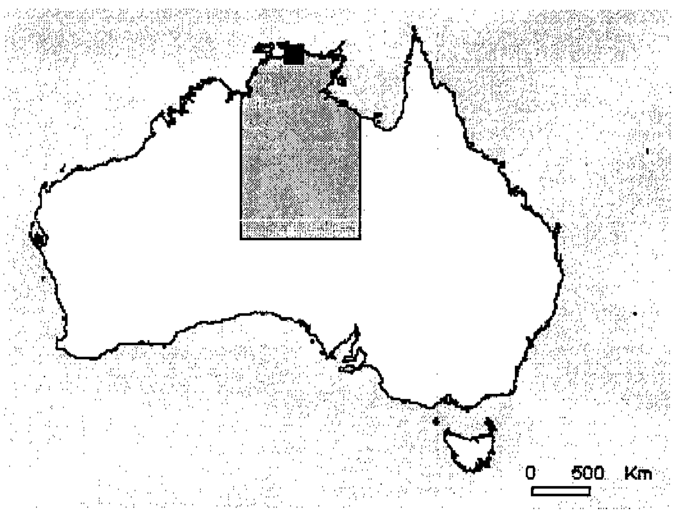

Figure 1: Location of the study area in the Top End of the Northern Territory

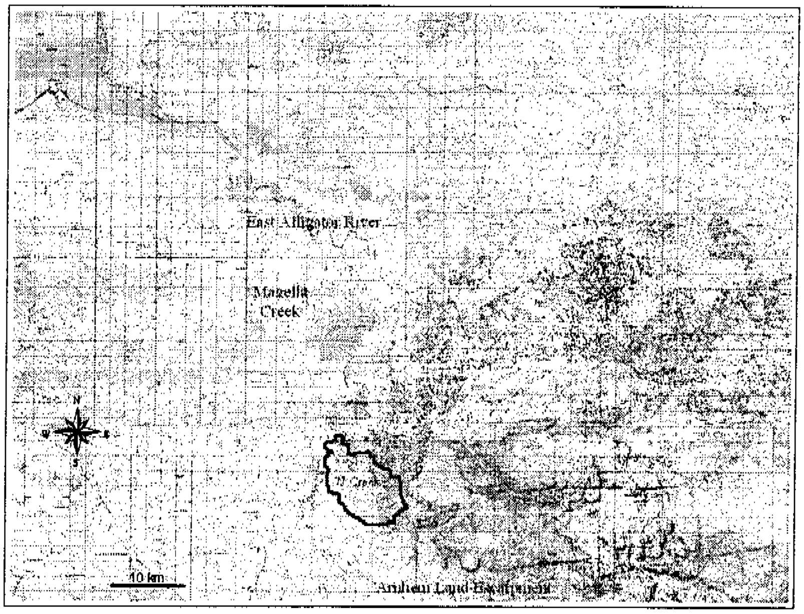

Figure 2(a): General view of the study area showing the 7J creek sub-catchment within the East Alligator River basin.

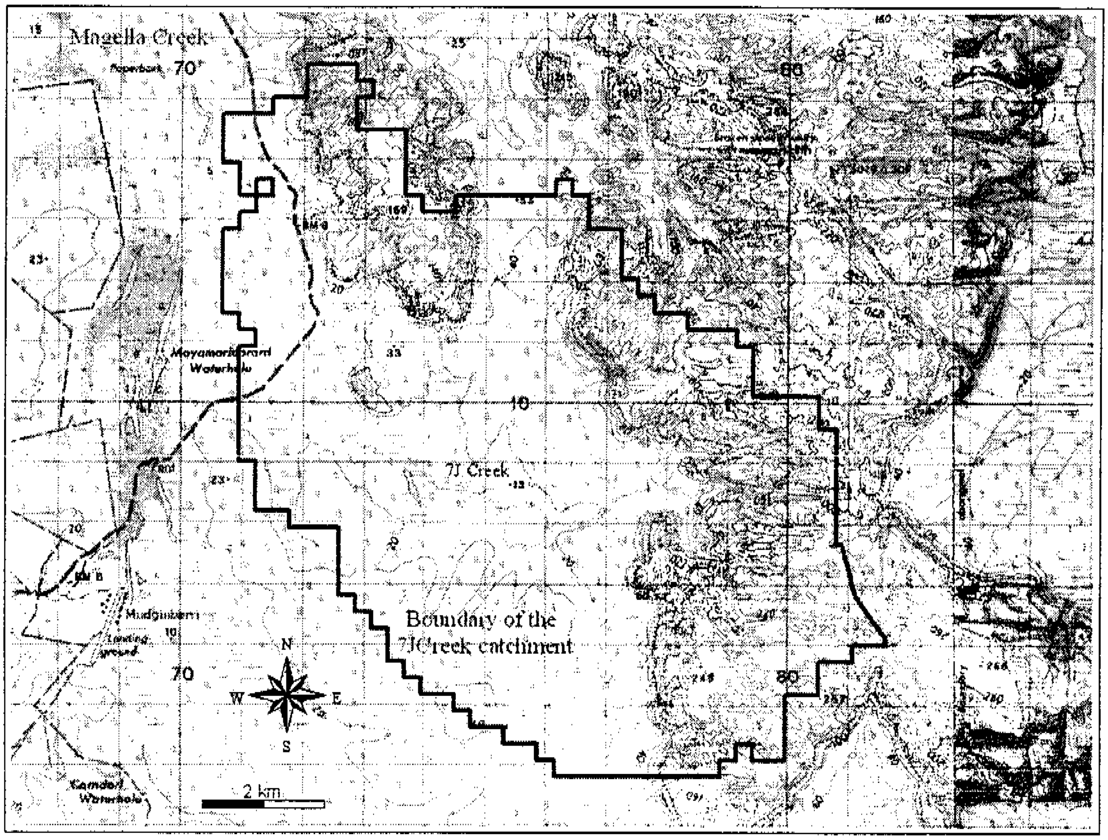

Figure 2(b): View of the study area showing the 7J creek sub-catchment within the Magela Creek system.

5.3 Data collation and derivation

5.3.1 Delineation of catchment

The 7J watershed was derived from the AUSLIG 9 second DEM data (projected to AMG using AGD66 datum) using the Hydrology extension on ArcView. This was overlaid with the 250K TOPO drainage layer to visually check that a sensible result had been returned. The derived watershed for 7J Creek (Fig. 3) had an area of approximately 76 km² and a perimeter of approximately 50km. The maximum flow length of the catchment was 16.5 km and the mean elevation 71m.

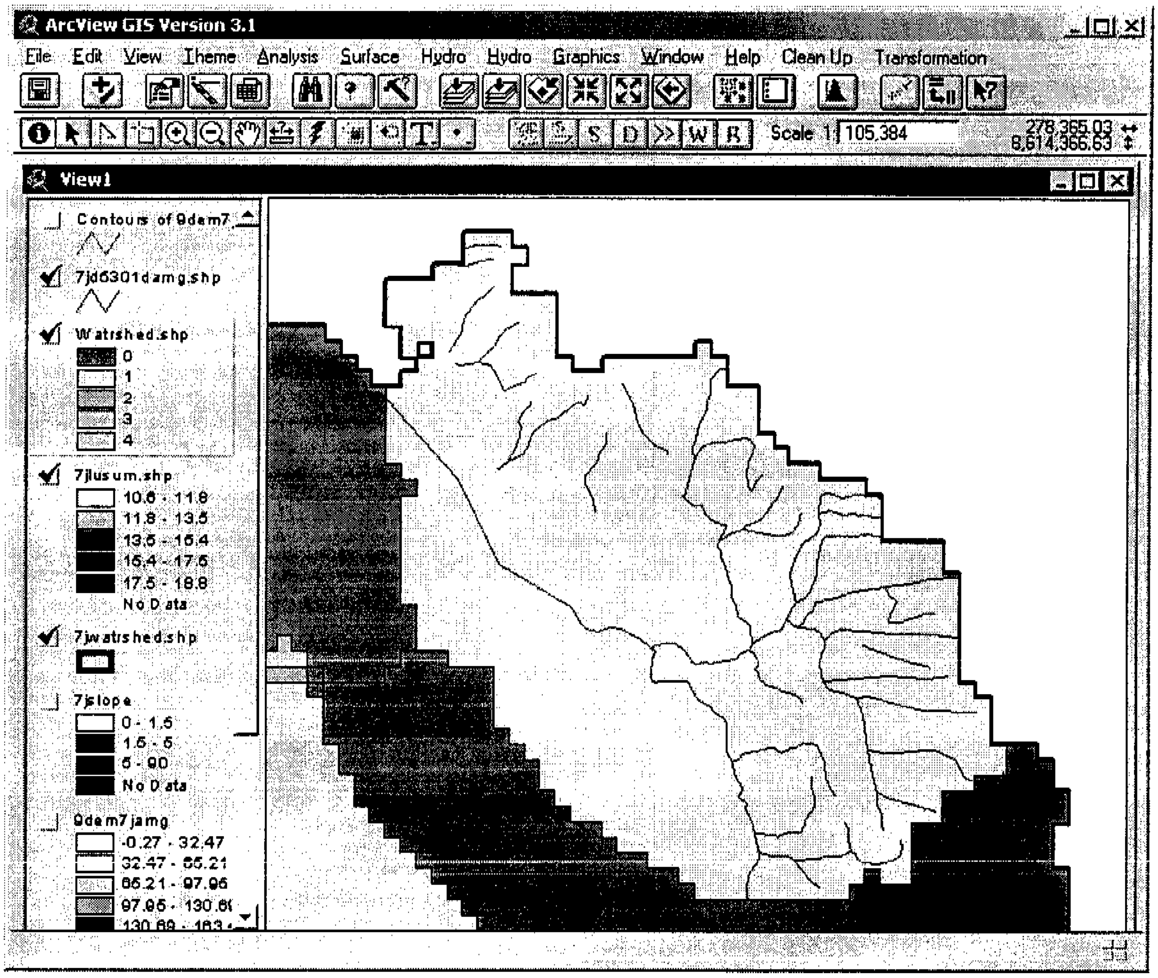

Figure 3: Watershed of 7J Creek

5.3.2 Land units

The land units map, having the potential to provide initial values for all principal factors, formed the focus of this investigation. The land units map was clipped to the boundaries of the 7J watershed and the land units within that area identified.

5.3.3 Data derived from land units

Landscapes are described in terms of land units. Identical land units share similar characteristics in terms of topography, soil and vegetation and can therefore be expected to display the same susceptibility to erosion. Extracting some of the parameters of the USLE from land unit properties is consequently a legitimate approach within the framework of rapid erosion risk assessment as land units can be either obtained from existing maps or by interpretation of remotely sensed data. Figure 4 shows the land units of the 7J Creek catchment.

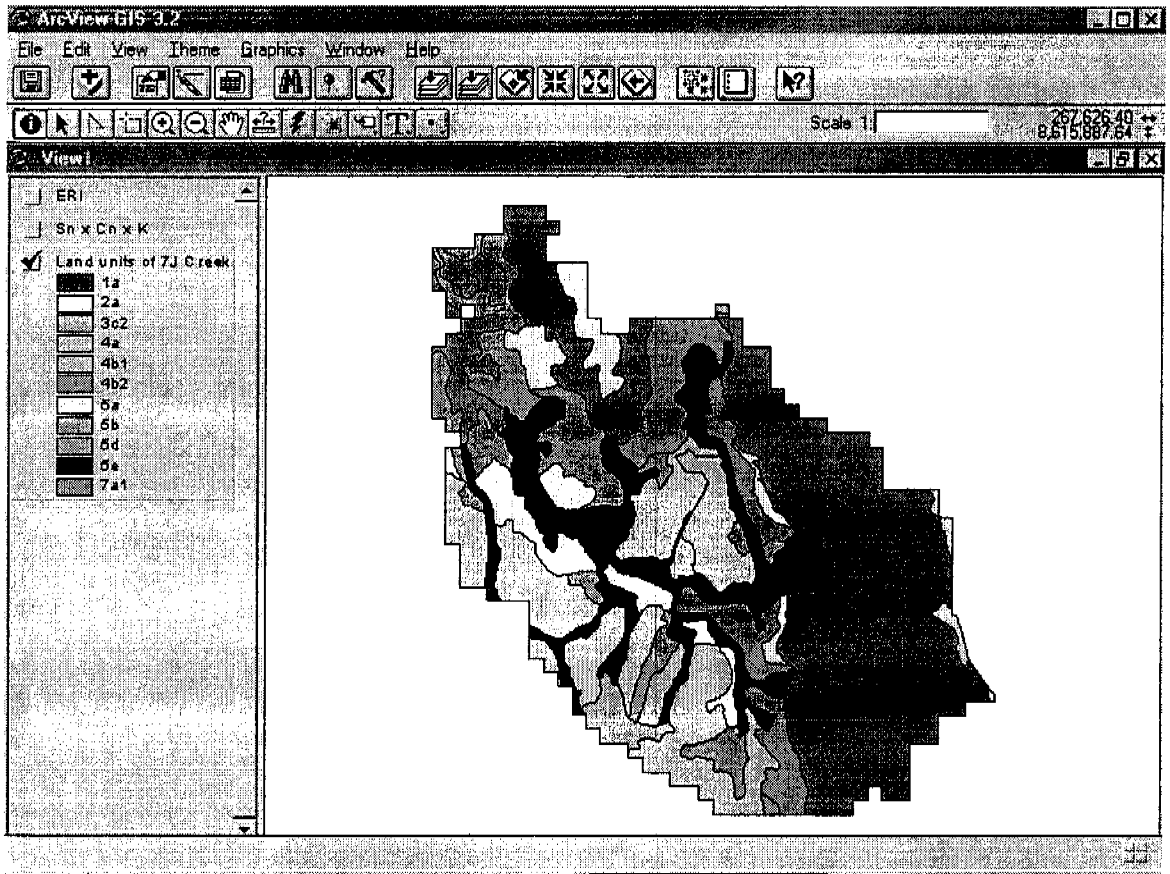

Figure 4: The land units of 7J Creek

Figure 5 lists the attribute table of the clipped land units (Fig. 4) where polygons were summarised (i.e. each land unit code is a region). Additional fields were added and populated/calculated as follows:

- S_n, the slope field, from Table 3
- K, the permeability field, from Table 1
- C_n, the cover field, from Table 5
- $S_n.C_n$.K contains the product of the values in fields S_n, C_n and K
- $S_n.C_n$.K_no contains the normalised product (i.e. all values of in S.C.K are divided by the highest value)
- ERI, the Erosion Risk Index, is obtained by sorting the values of $S_n.C_n$.K_no in 5 classes of equal range. Class 5 represents the highest risk of erosion.

File Edit Table Field Window Help

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Shape	Lucode	Count	Sn	Cn	K	Sncnk	Sncnk_nn	[illegible]
Polygon	1a	2	7.0	5.0	1.5	52.5	0.23	2
Polygon	2a	8	10.0	5.0	1.5	75.0	0.33	2
Polygon	3c2	1	0.5	4.0	7.3	14.6	0.06	2
Polygon	4a	3	1.5	6.7	9.1	91.5	0.41	3
Polygon	4b1	7	2.5	5.0	10.0	125.0	0.56	3
Polygon	4b2	1	3.5	5.0	10.0	165.0	0.73	4
Polygon	5a	6	1.5	6.7	2.4	24.1	0.11	1
Polygon	5b	15	1.5	6.7	4.8	48.2	0.21	2
Polygon	5d	6	7.0	6.7	4.8	225.1	1.00	5
Polygon	5e	5	1.5	10.0	3.9	58.5	0.26	2
Polygon	7a1	3	0.0	10.0	8.8	0.0	0.00	1

Figure 5: Amended attribute table of the land units of 7J Creek

The table (Fig. 5) consequently provides a translation of general characteristics of the landscape into erosion risk. Normalisation and the introduction of an index are justified as they simplify the process of ranking erosion risk attached to the various land units.

The red polygons in Figure 6 below highlight areas of highest erosion risk based on land units properties, an expression of erosion risk (S.C.K) derived from the USLE, and assumptions made on relationships between land units properties and the variables S, C and K. The slope factor S_n as well as the cover factor C_n and the permeability factor K, are derived from the description of the land units of the Magela Creek. These values and the ERI consequently apply to the whole area covered by each land unit. In Figure 6, the respective factors combine to produce a map of erosion risk, which cannot be readily inferred from any previous map. Red polygons, for instance occur in areas of steeper slope, however they are not found on the escarpment where the outcropping sandstone corresponds to a C_n which minimises the risk of erosion.

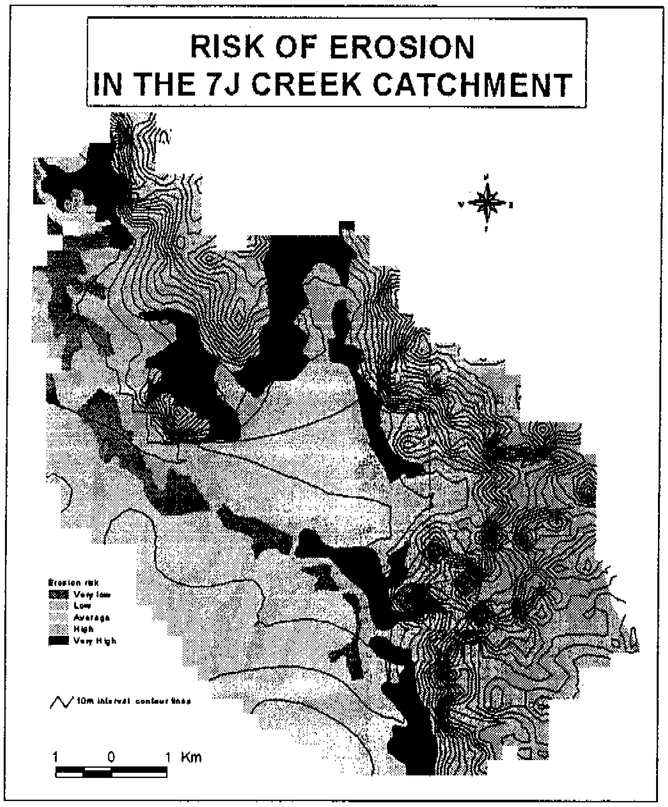

Figure 6: Map of 7J Creek showing the zones of relative erosion risk

6. DISCUSSION AND CONCLUSIONS

6.1 Discussion

In the chapter titled "Initial Model Factor Estimations" the parameters K, S_n and C_n of the simplified model of erosion proposed, are introduced. K was directly borrowed from the USLE, while S_n and C_n have little resemblance to traditional S and C parameters. S_n and C_n, however, like S and C in the USLE, reflect the influence of slope and cover on erosion.

The equation of the Erosion Risk Index (ERI) provides an initial framework that will evolve when field data become available.

$$ERI = S_n.C_n.K$$

An exponent p could be introduced to account for the relative influence of S on the erosion process, in the environment considered.

$$ERI = S_n^p C_n K$$

While this expression differs from the USLE approach "...there is some evidence that in the more extreme erosion conditions of the tropics, the slope effect is more exaggerated than in America, and that a figure of about 2 is more appropriate for the exponent ..." of S (Hudson 1976, 184) The embryonic model in this concept feasibility study uses p = 1.

So far this model has been described at the scale of a small catchment in order to benefit from a uniform rain regime (which makes the erosivity index redundant). In this state this equation can only be used to compare the risk of erosion within a catchment. The fieldwork required to assess the reliability of the model calls for extensive field work based on actual erosion measurements in a number of areas with different ERI.

The implementation of this model requires calibration of the exponent p after establishing relationships between S_n, C_n, K and landscape properties:

S_n would be better derived from slope data of a DEM while in Table 3 it was conveniently taken as the average slope estimated for each land unit;

C_n should take into account the protection provided by canopies as well as by ground cover (mineral as well as organic); and

K should be measured following standard procedures, implemented on test sites near the ERA Ranger mine

Land units and their description are central to this model. A geomorphic map providing more specific information on soil properties and topography would result in different polygons. The risk of erosion within each polygon would have a better chance of remaining constant as the classification criteria would better match landscape properties relevant to erosion. The slope, for instance, associated with each land unit (see Table 3) is unlikely to be sufficiently accurate for the purpose of detailed erosion risk assessment.

Remotely Sensed data will probably play a more important future role in developing a rapid risk assessment strategy. The challenge will then be to find surrogates which will translate remotely sensed data in terms of S, C and K. While S will be derived from a DEM, C and K should be linked to reflectance ratios typically used to characterise vegetation and soil such as SAVI (Soil Adjusted Vegetation Index).

6.2 Conclusions and further research

This report provides a practical initial framework from which to establish a strategy of rapid assessment of erosion risk based on a model successfully applied to a variety of environments for nearly half a century: the USLE. Although the basic USLE equation has been updated under the name of RUSLE (Renard 1994) its ability to provide low cost, general estimates of erosion appears to remain unchallenged. Although the USLE has a number of limitations (for example, it does not address streambank and gully erosion and does not account for redeposition) the simplicity of its mathematical expression is well suited to modifications aimed at making the best of scarce data which is a very important consideration in the Northern Territory.

The notes (see Appendix) on articles reviewed suggest that a GIS is well suited to erosion assessment. The variety of possible models (McCabe, 1997) does not affect the apparent preference of a number of authors for the USLE. Indeed the USLE and GIS were already applied to erosion assessment in the wet Tropics in the 80s (Hutacharoen, 1987). There is little doubt that a GIS is well suited to both short term and long term erosion assessment as it provides all the functionality necessary for the analysis and modeling of spatial data coupled with the storage and retrieval facilities of a database. In the short term, a GIS facilitates the integration of a model with dynamic remotely sensed data that can conveniently be combined for visual assessment first and later be digitised and merged with existing information through the model.

In the long term a GIS permits comparison of historical data in order to identify emerging patterns and refine the original model. As it stands this model has the potential to identify within a catchment high erosion risk zones and therefore to better allocate scarce resources where they are most needed either in terms of collection of field data or for the purpose of remediation.

Research aimed at improving the scope of this model should focus on:

- characterising the erosivity index in the Wet Dry Tropics;
- accounting for redeposition (Robinson 1977) and streambank erosion in order to develop a relationship between average erosion risk at catchment level and measured soil loss;
- refining the original model to rank catchments in terms of erosion risk within a region (the Alligator Rivers Region in this instance);
- identifying remotely sensed surrogates for C_n and K not only in the visual and Near Infrared Range but as well in the RADAR range in order to identify processes relevant to erosion specific to the wet season; and
- possible links between fire regime and C_n as late fires, for instance, are more likely to reduce the vegetation cover protecting the soil against the energy of the early Wet Season showers.

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8. APPENDIX: NOTES ON LITERATURE REVIEWED

This appendix provides brief notes on papers reviewed during the course of this study. They are included with a view to providing subsequent researchers with a resource to help them quickly identify authors and papers relevant to specific aspects of any future work which follows this study. They are arranged in alphabetical order by author name. See references for detailed citations.

Bischof (1996) describes Landassess Decision Support System (DSS): a new generation user friendly, GIS based, expert system. CSIRO created it with the help of specialists in a variety of domains. As it is designed to help graziers better manage their pastures and cattle, they were directly involved in shaping this DSS through workshops where their comments were used to match the properties of the system with the needs of its users. It features a Windows GUI and is built around an object-oriented knowledge base shell (Level 5 Object) and a GIS (PC archive). It incorporates as well a number of utility programs (e.g. LATools for maintaining the Landassess databases).

This system is a framework to evaluate sustainability of grazing management developed around:

a an iterative and evolutionary process (prototyping cycles, knowledge acquisition cycles, user interface development)

b prototyping

c a knowledge based approach following the model advocated by Hoppe in 1990 to handle situations where the required knowledge 'is not embodied in any formal scientific model'

The main functions of Landassess and its modules are:

a mapping at different scales

b land resource and climate database

c vegetation change and pasture knowledge base

d assessment of trade-offs: "What if" module

e user interface

f help system

The system design constraints were: availability of archival data, compatibility with end user needs, PC based platform, update ability and transferability, ease of access and use, conformity with software standards, good visualisation capabilities, the technical resourcing constraints of the DSS developers. The modelling approach was interdisciplinary. The characterisation of the landscape was based on:

a the concept of land unit (Christian and Stewart 1968; Aldridge and Robinson 1972)

b an assessment of soil erosion risk based on an adaptation of the Universal Soil Loss Equation (Wischmeier and Smith 1978) and an assessment (on a five class scale) of the type of soil erosion process a particular land unit would be susceptible to. These assessments took into account landform characteristics (slope, position), organic matter content, texture, vegetation.

Bocco et al. (1990) model gully erosion in volcanic terrains using both remote sensing and field observations. They can predict severe gully erosion risk.

De Roo (1991) uses the distributed model ANSWERS with the GIS package GENAMAP to estimate surface runoff and erosion. The large spatial variability of processes and attributes of these processes are ideally suited to his approach.

Desmet and Govers (1997) comment on the article by Mitasova et al. (1996) on the application of a method for the computation of topographic factors for USLE and stream power based model proposed by Moore and Burch (1986). Desmet and Govers consider that the conclusion of Mitasova et al (1996) is based on erroneous, inappropriate implementation of the topographic factor of the USLE for grid-based models. They are of the opinion that, theoretically, the classic USLE applies to landscape scale erosion modelling.

Devonport (1993) defines ARRGIS, a conceptual model at the heart of a GIS designed for the monitoring of potential hazards, primarily associated with radioactive materials and chemicals, in the Alligator Rivers Region. To perform this task this GIS had to accommodate changes in knowledge, technology, data types and user priorities. Structured approaches advocated by Clarke (1991) and Maguire and Dermond (1991) were followed to provide this prototype GIS with a number of fundamental features:

- "stubs structure" where software hooks allow the addition of software meeting specific needs (image processing and relational database management in this instance)
- no limitation on type of data by storing them in their original form and accuracy

ARRGIS deals with data at various resolutions, accommodates the storage of historical data, incorporates the concept of variable "theme resolution" and handles the temporal aspects of data. Instead of the conventional overlay model (superposition of themes at a given time) this GIS allows themes to be viewed in the past (monitored) as well as in the future (predicted) thus allowing the assessment of risk/hazard through the modelling of environmental processes.

Duggan (1991) assessed the impact of Ranger mine operation in terms of erosion and geomorphic stability of the lease area. Her main objectives were to monitor selected streams. The flow parameters were then used to establish flow-sediment discharge relationships to facilitate erosion monitoring. This method has limitations as it does not account for in-catchment sediment storage. Her study involves direct measurement of erosion on slopes using erosion plots and pins as well as measurements of sediment yields. The first method is logistically limited and results are difficult to extrapolate. The second method tends to underestimate erosion.

Remote sensing was not used in that study as it is better suited to high erosion rates and broad scale studies. Rainfall simulation is poorly suited to wet dry tropics as high intensity tropical rainfalls are difficult to reproduce. Models, whether they are simple like the USLE or more complex require substantial validation in each area of study. Yet empirical equations are valuable to provide first approximations of erosion.

Eight catchments were selected in the vicinity of Ranger, Nabarlek, Koongarra and Jabiluka mine leases. Four catchments are in areas of no mining, these natural catchments are: Koongarra creek, 7J creek that flows across Jabiluka mine lease, and Georgetown and Gulungul creeks near the Ranger lease. Factors affecting erosion in the natural lowlands are: burning (erosion higher on burnt sites), gravel lag (gravel deflects linear flow thus minimising rilling), litter cover (minimises erosion). On the natural lowlands there is no correlation between slope and erosion nor between vegetation and erosion. On lowland slopes, again, litter and gravel armour, more specifically, appear to be the main factors controlling erosion. The washloads recorded in the four natural catchments vary between 4 and 66 t/km^2/year depending on catchment and yearly rainfall. The erosion in the Koongarra catchment is nearly three times greater than in the 7J creek catchment. Erosion control on the lowlands must aim at stopping rilling before the appearance of gullies that are more expensive to stabilise. The siliceous sand of the slopes abutting the Arnhem Land Plateau is particularly prone to that type of erosion. This environment is unsuitable for roads and other infrastructures.

Evans & Loch. (1996) discuss a situation where a steep slope records less erosion than a near horizontal surface. The ERA Ranger cap site has a slope gradient of 2.8% but is compacted and has finer grain size. A batter site surface, on waste rock dump, with a slope of 20.7% has an erosion rate 1/2 the one on the cap site. Parameter values are derived for the RUSLE and these are used to compare differences between the sites and explain differences in erosion rate. Differences in rate of erosion are attributed to poor infiltration and increased runoff due to compaction and finer grain size of the cap site.

Evans et al. (1991) define two categories of useful erosion prediction models. USLE, WEPP, GUESS, CREAMS are soil loss prediction models on short or long term basis. Topog, SIBERIA, ANSWERS that are topographic evolution models. On mine sites, cover intervenes in the USLE. Erosion models used to design post-mining landscapes fall in two groups: soil loss prediction and topographic evolution models. USLE has been successful on cultivated land but the variables are site specific in mines. R and K are the controlling factors.

Fitzpatrick (1993) emphasises the need to integrate land unit mapping and satellite remote sensing. He proposes three methodologies for monitoring soil erosion hazard. He considers that vegetation cover changes provide information to assess soil erosion hazard and that remote sensing is ideally suited to monitor vegetation cover changes. The method he uses requires three yearly sets of satellite data and coincident ground truthing. The results will be in the final report of GINGERS project.

Hinton (1996) discusses the requirements of integrated software systems to combine RS data with vector datasets. GIS and RS during the past decade moved increasingly from an empirical to a modelling approach. GIS, in the future, will need discipline specific modelling tools, seamless integration with office software, compatibility with high resolution RS and expert systems.

Kemp (1993) explores the specific features of spatial data with emphasis on digital data. Spatial data need to be stored and manipulated in unique, new ways. Point data can correspond to discrete objects or individual measurements or continuous phenomena. The second type implies a linear, or at least regular, change between two consecutive points (in elevation measurements for instance). An alternative approach to visualising continuous phenomena consists of dividing the space into a set of contiguous regions (for soil maps for instance).

A map is often a relatively poor choice as a source of precise digital data because of two "cartographic license" techniques:

- the practice of slightly displacing overlapping objects (parallel roads and rivers for instance); and

- generalisation to reduce the amount of information displayed (meanders in a river). In databases these cause indiscriminate locational errors whose significance depends upon the applications in which the data are used

Problems arising from integrating digital data from large and small scale maps are reflected in the actual change in width, and subsequent locational uncertainty, of a line drawn on maps at different scales. For any but the largest scale maps, the question of projection is critical. The accuracy of map projection transformation functions, normally built into commercial GIS, is rarely disclosed.

The errors introduced by remotely sensed data are sensor specific and largely vary with the type of processing carried out (while orthophoto quads provide accurate data, air photos in general suffer from distortions). The format in which data are stored used to be a major hurdle to file exchange. This situation is rapidly changing for two major reasons:

- proprietary data structures and file formats can increasingly be transformed into an intermediate structure that can be imported by other programs
- the USA are developing structure standards (Spatial Data Transfer Standards), for spatial data transfer. GIS vendors, and their customers, who wish to do business with US federal government, have to comply with SDTS. Europe, and many other countries, are introducing similar policies to facilitate spatial data transfer.

Korte (1994) reviews four leading GIS software (ARC/INFO, Geo/SQL, GENAMAP, MGE). ARC/ INFO offers flexibility of platform and operating system. A 17-step approach to GIS project implementation is outlined and it identifies major pitfalls: failure to define goals, no long term planning, and failure to anticipate problems. A qualifier is required to indicate source of data, reliability and accuracy to avoid a false sense of accuracy given by GIS measurements. The scale selection for a GIS defines its range of applications once and for all.

McCabe (1997) studies erosion hazard in a catchment by calculating an erosion index based on the estimation of the following key hydrological parameters:

- local slope estimated by steepest descent approach Deterministic 8 (D8) and finite difference approximation
- flow through a catchment calculated by "D8" and multiple flow path (MFP), alternatives are random eight node (Rho8), DEMON and Tarboton's technique
- runoff mechanism is modelled using the uniform rainfall excess (URE) and the saturation overland flow mechanism (SOF)
- critical wetness index

This study is carried out in ARC/INFO. Two software packages: TAPES-G (Terrain Analysis Programs for the Environmental Sciences - Grid version) and ANUDEM are compared and through them a number of algorithms used to evaluate the hydrological and topographical parameters necessary to assess erosion hazards.

There are numerous models to evaluate erosion: USLE, SIBERIA, WEPP, Hairsine -Rose, EROS among others. EROS and USLE are conceptually different to the other models named previously. EROS, for instance, makes no attempt at estimating the net erosion, but instead derives an erosion index.

A number of parameters used by EROS are reviewed. The selection of runoff mechanisms and flow algorithms (D8, Rho8, MFP, DEMON) is discussed. Shortcomings of the steady state assumption are revealed when comparing the shapes of theoretical catchment slopes with identical wetness indices. The impact of grid scale variation can be estimated through a cumulative area diagram. This diagram normally shows the three distinct regions of a catchment hydrological structure. If one appears to be missing the grid cell size is inappropriate for the area studied. Some methods appear to be a lot more sensitive to variation in catchment parameters. The "D8" method gives comparatively much higher erosion indices than the Finite Element method when slope changes (as a result of change in grid cell size for instance).This raises a crucial question: what is the correct technique to use when calculating the slope? The increase in upslope contribution similarly changes with grid size. Here the Multiple Flow Path algorithm gives higher values than the D8 method. Both methods seem to plateau for a grid size of 100m that implies that they are no longer sensitive to changes in topography.

To conclude the author remembers Grayson and Moore's words "...The models used, while appearing conceptually sophisticated, are based on assumptions that are often invalid or questionable ...." Among the recommendations, scale and resulting systematic errors are most prominent as they will affect all results.

Milne et al (1997) use TIN & 3D representations of channel topography on ArcInfo to map, at a large scale, 7 short sections of a gravel-bed river. The derived surface models are then used to estimate sediment budget. TIN is most appropriate for that task. The need for accurate topographic surveys extending across floodplains is stressed. Topographic bed boundaries can be used to sample discrete variables such as grain size. Studies of channel change must incorporate past adjustments and call for a modelling approach.

Mitasova and Hofierka (1997), in a response to a comment by Desmet and Govers (1996), suggest that the USLE modification is an appropriate generalization for complex terrain. Desmet's proposal has severe limitations as it neglects important processes such as deposition. The classic USLE (nearly 30 years old) was not intended for detailed mathematical erosion modelling. Empirical equations should be replaced by distributed process based models identified and explained by Meyer and Wischmeyer (1969).

Mitasova et al (1996) model erosion in complex terrains. In this situation GIS requires a high resolution DEM, reliable estimation of topographic parameters and an appropriate formulation of erosion models. The construction of the flow lines and upslope contribution rely on a vector-grid approach.

Pickup and Chewings (1990) map and predict soil erosion patterns using Landsat images. They describe recent broad scale conceptual and mathematical models of soil erosion on flat arid lands. The end result is a translation of standard Landsat MSS data into soil stability index.

Singh (1991) uses GIS and mapping with Landsat MSS data to grade erosion risk (rainfall erosivity, slope, soil erodibility and vegetation cover) into four categories (scarcely to highly vulnerable).

Wells (1979) documents land resource mapping, erosion and soil erodibility studies conducted by the Territory Parks and Wildlife Commission of the NT during the dry season of 1978 in the Ranger, Jabiru and Jabiluka area. Soil erodibility in the Magela catchment is rated as slight to moderate due to the rapid to very rapid infiltration rate in undisturbed soil situations. This in turn minimises run off. During the 1978 dry season the most significant areas of erosion were in Jabiluka where, by opposition to Ranger, the soil is essentially gravel free. The 15 land systems are:

Amhurst	Bedford	Bundah	Buldiva

Cyperus	Effington	Jay	Kay
Keefer's Hut	Knifehandle	Kosher	Krokane
Kysto	Queue	Pinwinkle	

The different terrains and corresponding land systems in that area are:

Plateau Surface	Alluvial Plains on Freshwater Sediments
Rugged Terrain (Plateau side slopes)	Alluvial Clay Plains and Swamps
Undulating Upland Terrain	Littoral areas

Wilkinson (1996) despite major new developments in integration of GIS and RS considers that problems remain: choice of appropriate data structures, procedures for handling error and uncertainty. During the next 10 years RS data will become a lot more complex due to multi-sensor, hyperspectral, multi-view angle and time series approaches. Some fundamental problems will result from little consensus on data structures and management of error and uncertainty. On top of conventional cartographic data, RS data of enormous dimensionality, revealing unpredictable complexity, will be input into GIS.

Wischmeier and Smith (1978) developed for the US Department of Agriculture the Universal Soil Loss Equation (USLE). It predicts soil loss due to erosion for combinations of crop system and management practice, soil type, rainfall pattern, and topography. This equation groups the many interrelated factors into six groups: rainfall and runoff factor (R), soil erodibility factor (K), topographic factor (LS) combining a slope-effect (S) and a slope-length effect (L), cover management factor (C), support practice factor (P). The USLE is based on half a century of erosion research in the USA. Tables and charts are available. The USLE models soil losses from sheet and rill erosion primarily for agricultural sites but can be extrapolated to non-agricultural environments. However this model does not compute sediment yields from gully, streambank and streambed erosion.

Xongchao (1988) maps water erosion risk with ARC/INFO using the Universal Soil Loss Equation (USLE) defined by Wischmeier and Smith (1978). Landsat MSS provides land cover information that combined with soils, digital elevation and rainfall are input into the GIS.

Walsh et al. (1998), after describing a number of examples of relationships between landform and processes in hydrology, concentrate on RS and GIS in environment analysis. They state how a GIS generated DEM allows the calculation of indices (slope curvature, index of saturation potential, index of landform, fetch and directional relief indices) to quantify the characteristics of a landscape. The calculation of these indices based is carried out by the GIS (slope, height of a target cell relative to its neighbourhood as a surrogate for exposure). Optimum spatial scales for representing terrain and plant relationships are derived from the combined use of GIS based DEM and plant biomass estimated from satellite digital data. These are just a few of the many examples of how GIS and RS can produce a numerical description of a landscape which then allows modelling for a variety of purposes.

Other studies combining GIS and modelling/predicting erosion include:

- Bagheri et al. (1990): IR photography for site selection
- Bergsma (1986): aspects of mapping in rain erosion hazard catchment survey
- Carrera et al. (1991): high fidelity DTM to partition terrain into slope-units
- Flacke et al. (1990): USLE in conjunction with DTM to map soil loss due to erosion

- Garg & Harrison (1990): GIS for hydrologic and erosion modelling
- Hutachaoren (1987): GIS to assess soil loss in watershed in Thailand based on USLE
- Jong & Riezebos (1992): multitemporal RS data and empirical erosion model to assess erosion risk
- Law et al (1991): GIS to monitor and predict lake shoreline erosion
- Meijerink et al. (1986): RS and GIS to model erosion and sediment yield
- Moussa (1991): GIS to model sediment yield from large watersheds
- Nossin (1989): MSS data resolution too coarse for hazard surveying, potential of radar
- Simonett et al (1987): environmental database to assess problems nation wide in Uganda
- Suryana (1992): basic mapping units and inductive erosion model in GIS