1 Introduction and background

1.1 Introduction

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

1.2 Study area

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

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

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

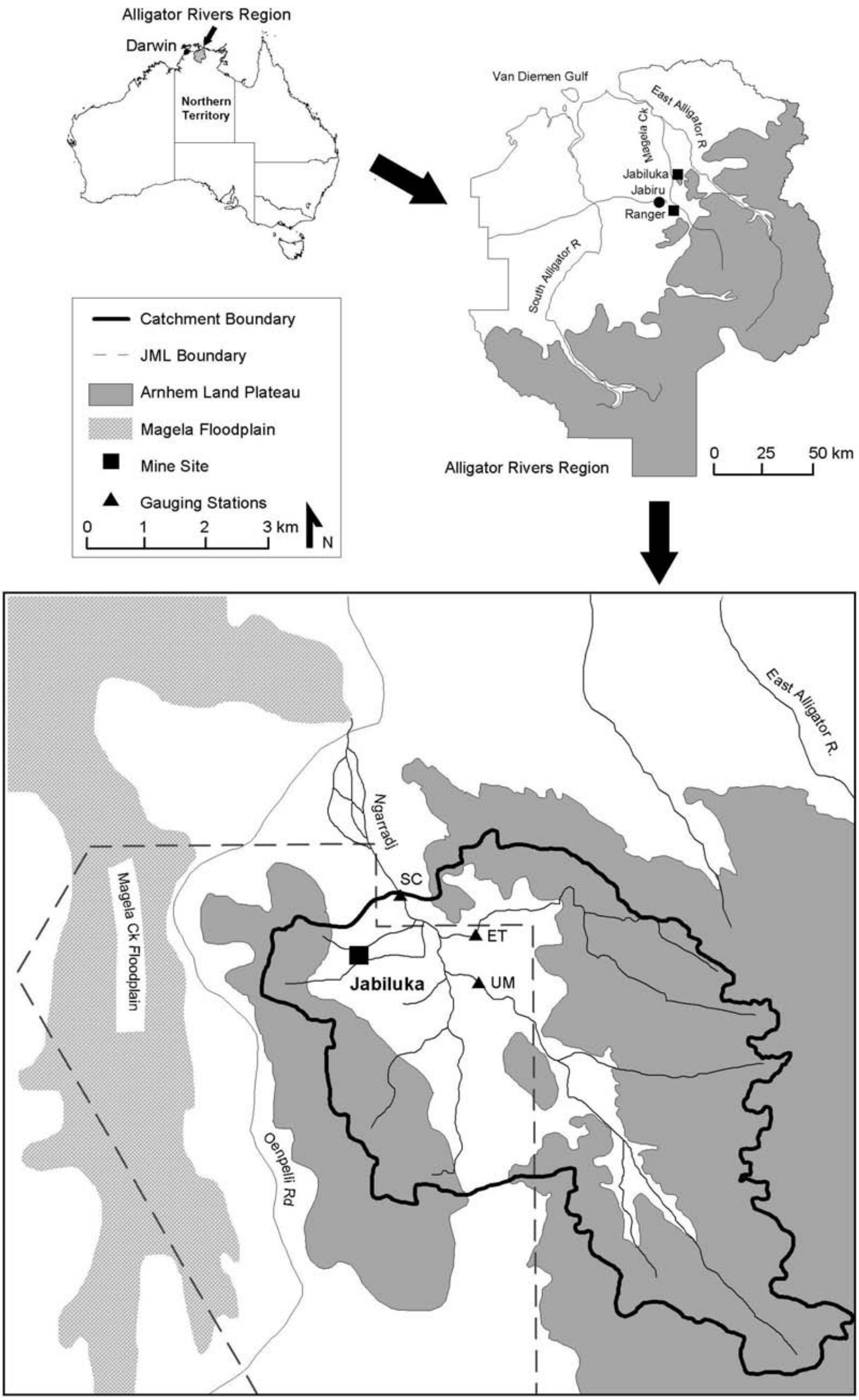

Figure 1 Location of the Ngarradj catchment in the Northern Territory of Australia where ET = East Tributary, UM = Upper Main and SC = Swift Creek

1.3 Background

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

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

1.3.1 Erosion hazard models

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

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

1.3.2 Landform evolution models

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

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

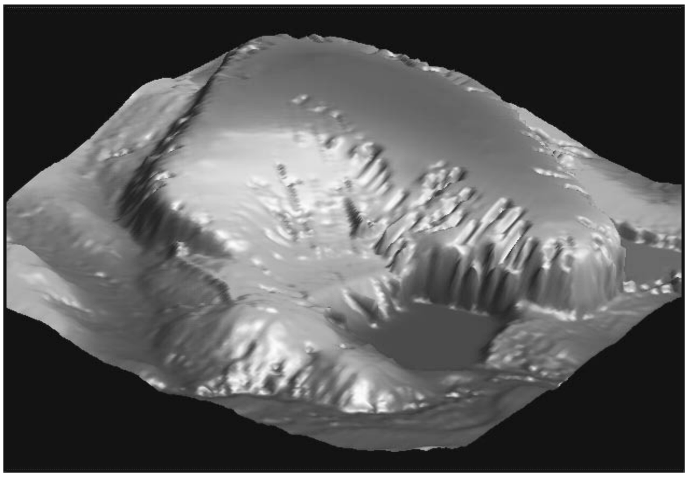

Figure 2 Modelled landform evolution on a proposed post-mining landform, showing the development of gullies and depositional fans (after Evans 1997)

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

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

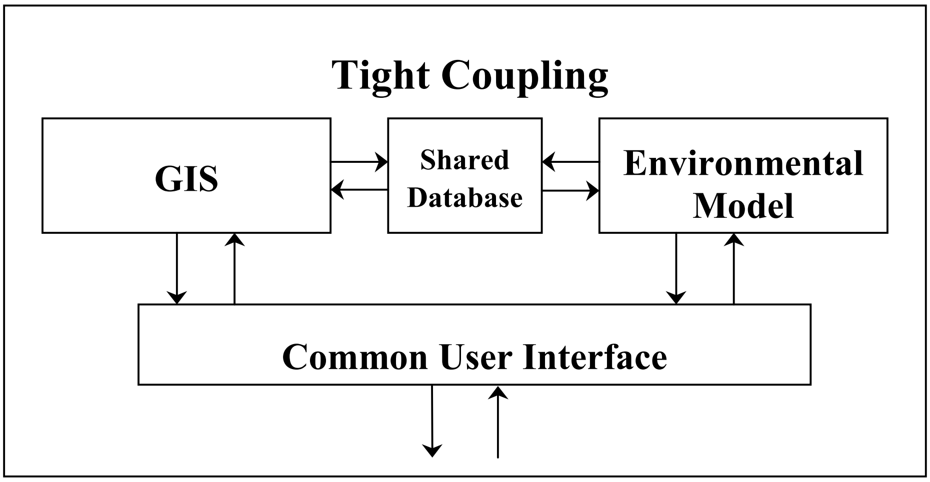

Figure 3 A conceptual diagram of the tight coupling approach to model/GIS integration (after Fedra 1993)

1.3.3 Basin analysis with GIS

1.3.3.1 Preparation of DEMs

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

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

1.3.3.2 Standard GIS basin analysis tools

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

grid1 – grid2 = grid3

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

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

grid3 < grid4

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

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

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

1.3.3.3 Geomorphometric measures for assessing catchment change

Geomorphometry, defined as the 'quantitative treatment of the morphology of landforms' (Morisawa 1988), has expanded significantly since the studies of Horton (1945) and Strahler (1964). The advent of the DEM has allowed geomorphometry to not be limited to the time-consuming measurement of landform properties from contour lines on topographic maps. The DEM has allowed the development of algorithms that rapidly derive such measures and has also allowed the definition of a number of new morphometric measures (Nogami 1995). The width function, hypsometric curve, cumulative area distribution and area-slope relationship are four geomorphometric measures that can be rapidly derived from a DEM and have been shown to be important measures of catchment geomorphology and hydrology (Perera 1997). These descriptors have also been successfully used to quantify and compare SIBERIA derived landscapes with natural landscapes (Hancock et al 2000a). This study represents the first attempt to apply these measures to assessing the impact of mining on catchment evolution.

Hypsometric curve

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

Width function

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

Cumulative area distribution

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

Area-slope relationship

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

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

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