ArcEvolve: A Suite of GIS Tools for Assessing Landform Evolution

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Abstract. This paper describes the tools developed to link the SIBERIA model with a GIS. SIBERIA simulates the evolution of landforms within a catchment using digital elevation data. Integration of SIBERIA with a GIS provides easier access to the model for non-specialist users, and also extends model functionality. The complexity of the model means that integrating the two technologies using an 'embedded' approach is not feasible. However, by using a 'tightly-coupled' approach the model and the GIS retain separate executables and memory space but share the database and provides a single integrated interface to the user. In addition, this approach enables the processing and analytical capabilities of the GIS for the analysis of SIBERIA output. The suite of tools developed to link SIBERIA with the ArcView® GIS package have been assembled into an ArcView® extension named 'ArcEvolve'. The functionality ArcEvolve adds to the GIS graphical user interface is grouped into two parts. The first group contains components relating to the user interface including; (i) import/export utilities for the different SIBERIA native format files; (ii) access through dialog boxes to the creation and management of a SIBERIA parameter database; and (iii) running the model. The second group includes functionality for the geomorphometric analysis of digital elevation data, the primary output of SIBERIA. The geomorphic statistics adapted for ArcEvolve include the width function, hypsometric curve, cumulative area distribution, area-slope relationship, denudation rate and volumetric change. These descriptors are important measures of catchment geomorphology and hydrology and have been successfully used to quantify and compare SIBERIA derived landscapes with natural landscapes.

1. INTRODUCTION

Prediction of the future evolution of landforms is one of geomorphology's primary research goals and is an important tool in impact assessment. 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 attempt to quantify the erosion and deposition occurring within a catchment. Landform 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 modelling 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). Landform change can subsequently be statistically assessed using geomorphometric techniques.

SIBERIA is a computer model designed for examining the erosional development of catchments and their channel networks (Willgoose, et al., 1989). The model operates on an elevation grid and integrates simulation of erosion processes, theoretically and experimentally verified at small scales, with a physically based conceptualisation of the channel growth process (Willgoose, 1992). Topographic change is represented on the digital elevation model (DEM) by changes in node elevation due to sediment import from upstream grid cells and sediment export to downstream grid cells (Willgoose and Riley, 1998). Hydrology is modelled as a function of the contributing catchment area for each cell according to a runoff constant (Coulthard, 2001).

Geomorphometry, defined as the "... quantitative treatment of the morphology of landforms...", (Morisawa, 1988) has been successfully used to quantify and compare SIBERIA derived landscapes with natural landscapes (Hancock, et al., 2000). The advent of the DEM has allowed geomorphometry to not be limited to the time-consuming measurement of land form properties from contour lines on topographic maps. The DEM has allowed the development of algorithm's that rapidly derive such measures and has also allowed the definition of a number of new morphometric measures (Nogami, 1995). The width function, hypsometric curve, cumulative area distribution and area-slope relationship are four geomorphometric measures that can be rapidly derived from a DEM and have been shown to be important measures of catchment geomorphology and hydrology (Perera, 1997).

Geographic information systems (GIS) offer a wide range of raster data processing capabilities and a clear means for organising and visualising data from a number of different formats (Rieger, 1998). Linking the SIBERIA landform evolution model and geomorphometry with GIS will therefore provide 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. The SIBERIA landform evolution model is computationally intensive and consequently does not lend itself to interactive use. Combining this model with a GIS will provide for improved usability of and also extend the functionality of the model. The complexity of the model means that integrating the two software applications using an 'embedded' approach is not practical. However, by using a tightly coupled approach the two applications will essentially remain separate but will share a user friendly front end and database. Furthermore, by using this approach the processing and analytical capabilities of the GIS will be available for the analysis of SIBERIA output.

This paper describes the development of an ArcView® GIS extention, 'ArcEvolve', that provides a GIS-based user interface for the SIBERIA landform evolution model and also includes tools for the geomorphometric analysis of elevation data. Integrating SIBERIA with a GIS strengthens the modelling process, as the GIS can assist in the derivation, storage, manipulation, processing and visualisation of geo-referenced data (Boggs, et al., 2000). ArcEvolve provides tools that can be used for assessing the impact of human landuse activities on catchment geomorphological and hydrological processes. However, ArcEvolve is a prototype that is to be tested through application to the assessment of the impact of the ERA Jabiluka Mine, Northern Territory, on the Ngarradj[1] catchment (Boggs, et al., 2001).

2. ARCEVOLVE

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

ArcEvolve adds two menus to the ArcView® 'View' document graphical user interface (GUI). The first, 'SIBERIA', contains a number of items that; (i) allow SIBERIA native format files to be imported and exported; (ii) provide access to dialog boxes for the creation and management of a SIBERIA parameter database and (iii) run the model. The second menu, 'Geomorph', contains functionality for the geomorphometric analysis of digital elevation data (the primary input and output of SIBERIA).

[1] **Ngarradj**: 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 com 2000)

2.1 SIBERIA Interface

The method used to link the SIBERIA landform evolution model with a GIS is termed 'tight coupling'. Tight coupling involves integration of GIS and environmental models by providing a common user interface for both the GIS and the model. The 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 (Loague and Corwin, 1998). 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).

The standard input/output file used to run the SIBERIA model is a 'restart' file. The restart file has a plain text format and contains the DEM data and sufficient parameter information for SIBERIA to be able to restart from this file without having to re-input parameters (although the parameters controlling the length of the run can be altered). This file is the only file output from SIBERIA, however, a compressed binary form of this file can also be input. Currently ArcEvolve will only interact with the more commonly used plain text format restart file. Options within the ArcEvolve extension allow the user to import elevation data from the restart files as ARC/INFO grids, with the extensive parameter information either stored within an associated parameter database, or ignored if the user wants to examine only the elevation properties of the file. Conversely, ARC/INFO grids can be exported as restart files either with the associated parameter set, or a standard initial parameter dataset.

The restart file has space allocated for up to 80 individual parameters which relate to the running of the model, erosion, hydrology, channel and tectonic characteristics of the landform and design of the DEM. These parameters are stored by the GIS within tables with each record associated with a grid. This allows groups of spatially related parameters to be stored within individual tables, providing a more efficient method for managing modelling projects. A series of dialog boxes have been designed to allow the user to access the individual parameter values associated with a grid. The dialog boxes group related parameters and can be accessed for a selected grid from the View document. Parameters can also be copied from one grid to another and deleted from the View document. This simplifies the database management, although the tables can be managed similarly to standard ArcView® tables.

An additional file used by SIBERIA is the 'boundary file' which contains boundary information for an irregularly shaped region. Boundary files are plain text files that define areas inside and outside a region and the catchment outlet(s) of the region. ArcEvolve provides functionality to generate boundary files from ARC/INFO grids. Catchment outlets can be defined by the user or, if the grid is an elevation grid, automatically created. Boundary files can also be imported as

ARC/INFO grids. However, boundary files do not contain georeferencing information and as such require the user to input the coordinates of the lower left hand point of the grid.

Spatial variability is included in SIBERIA's assessment of landform evolution through the definition of regions within the DEM for which individual sets of erosion and runoff parameters are applied. 'Region files' are identical in format to boundary files being composed of the x and y coordinates of the boundary of the region. The region boundary files remain constant throughout the simulation period. The individual sets of erosion and hydrology parameters are stored in a single generic 'erode' file which subsequently relates to each region file, applying the particular set of parameters when SIBERIA operates on the defined region in the DEM. Linking SIBERIA with the GIS allows the rapid derivation of region files.

ArcEvolve is a GIS-based front-end for the SIBERIA model. As such, running the model from the GIS simply involves defining the run parameters and launching the model (Figure 1). The GIS then translates all input data into a readable format for SIBERIA and runs the model. SIBERIA produces output restart files at intervals defined in the run parameters by the user. ArcEvolve includes options to either periodically check for output and add it to the View document, or to wait until the model run is finished before adding all data to the View document.

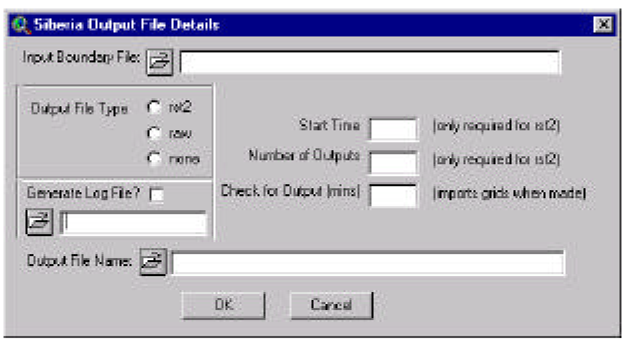

Figure 1: The dialog box from which SIBERIA is run within ArcView®.

2.2 Geomorphometric Analysis

The standard geomorphic statistics used in previous studies to assess landform evolution have been the width function, hypsometric curve, cumulative area diagram and area-slope relationship. These statistics have been adapted for implementation within the ArcView® GIS package and have been included in the Geomorph menu of ArcEvolve. The output of each function is an ArcView® chart and table. However, the data can be easily exported from ArcView® into more graphing or statistical packages for final presentation or further analysis. ArcEvolve also provides a standard cut-fill option to quantify volumetric changes in elevation grids and an option to calculate the denudation rate between two output grids.

1.1.1. Hypsometric Curve

The hypsometric curve, describing the distribution of area with elevation, provides a quantitative means for characterising the planimetric and topographic structure of a catchment (Luo, 1998). The hypsometric curve therefore provides a method for analysing the geomorphic form of catchments and landforms by characterising the distribution of elevation within a catchment (Willgoose and 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 integral, the area under the curve itself, also provides a measure of dissection of a landscape. The hypsometric curve is therefore an important tool when analysing landform evolution over geologic time scales.

The hypsometric curve option in ArcEvolve is an adaptation of that developed by Kohler (2001) and is calculated 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 output includes the hypsometric integral as well as a simple chart of the hypsometric curve and a table containing the relative elevation and area information. Normalisation of the curve means that catchments of various size can be directly compared. Figure 2 shows the hypsometric curve for three catchments that represent increasingly large portions of the Ngarradj catchment. The decreasing hypsometric integrals of the increasingly large catchments demonstrates the relationship between catchment maturity and hypsometric curve.

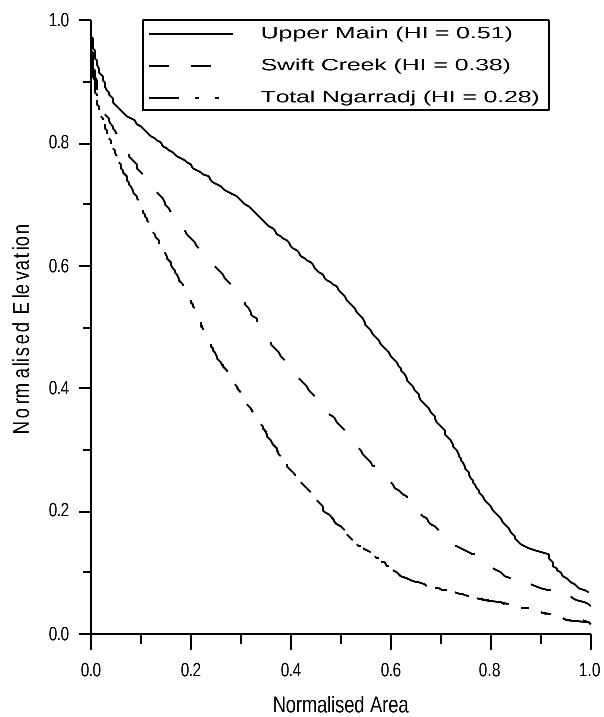

Figure 2: The hypsometric curves and integrals (HI) for the Upper Main, Swift Creek and Total Ngarradj catchments.

1.1.2. 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 was originally 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 and 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 original form and simplified form of the width function have been adapted for implementation within ArcEvolve (Figure 3 and 4). The stream network for the original form of the width function is derived within the algorithm by thresholding the drainage area required to generate a stream (Jenson and Domingue, 1988). Implementation of the width function in ArcEvolve allows the user to define the drainage area required to create a stream. This has important implications for the shape of the width function and requires the user to have a good understanding of the input data to interpret the results. Initial applications of the ArcEvolve form of the width function have found that the original form of the width function is more sensitive to changes in catchment structure than the simplified form (Boggs, et al., 2001).

Calculation of the width function in ArcEvolve also requires the user to select the distances from the catchment outlet at which the 'width' is measured. The distance selected should attempt to minimise noise associated with choosing an interval that is too small whilst not being too generalised to provide any useful information.

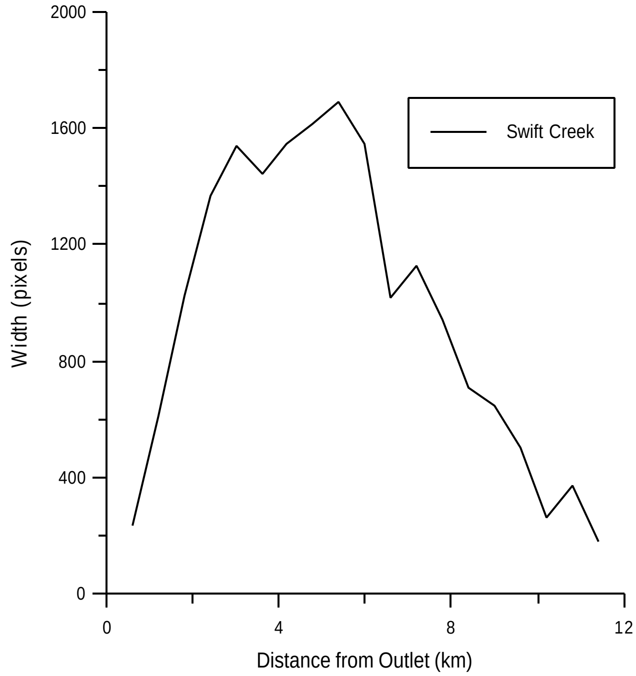

Figure 3: Simplified width functions for the Ngarradj catchment.

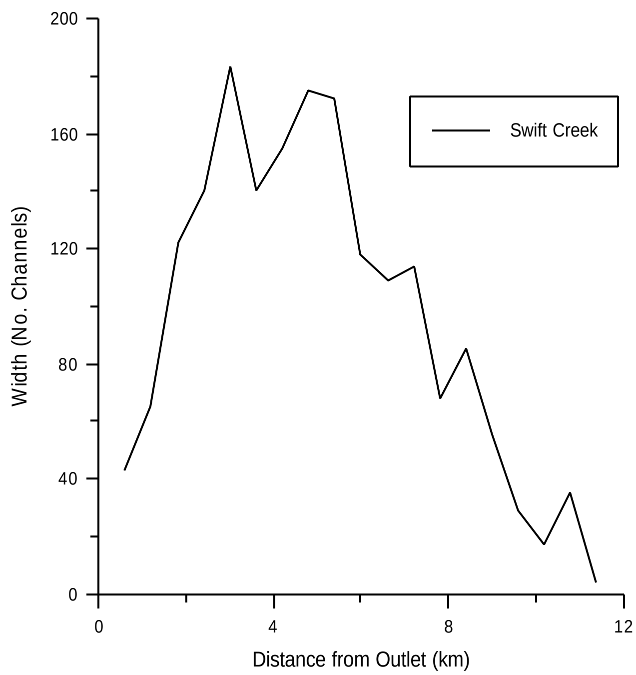

Figure 4: Original width functions for the Ngarradj catchment where stream channels are defined as areas with drainage areas greater than 10 ha.

1.1.3. 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 and Bras, 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 and 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.

The cumulative area distribution is calculated as the area of the catchment that has a drainage area greater than or equal to a specified drainage area (Perera and Willgoose, 1998) (Figure 5). The cumulative area distribution is calculated within ArcEvolve from an elevation grid. The cumulative area distribution can be used within an impact assessment to provide information on the distribution and relative importance of areas dominated by rainsplash or interrill erosion processes, channelised flow and large channels.

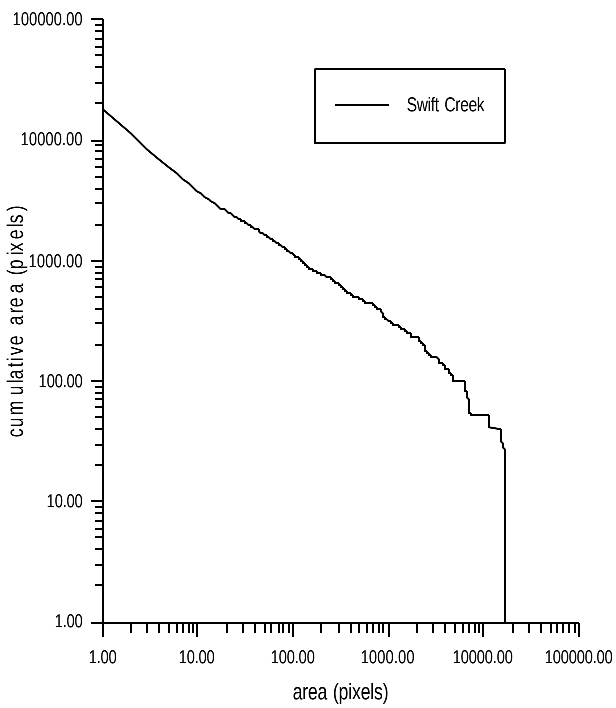

Figure 5: The cumulative area diagram for the Ngarradj catchment.

1.1.4. 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 and Bras, 1994, Willgoose, et al., 1991). The area-slope relationship for a catchment has been reported by many authors as having the form;

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

The area-slope relationship has also been shown to be an effective method for comparing the elevation properties of different catchments.

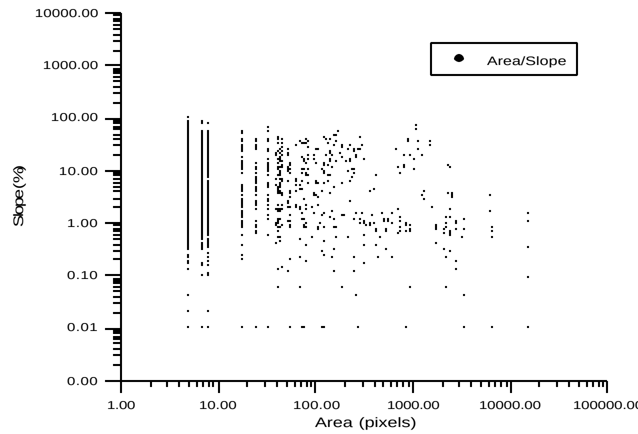

Figure 6: The slope area relationship for the Ngarradj catchment illustrates the complexity of distribution of slope angles in the Ngarradj catchment.

3. APPLICATION

ArcEvolve has been designed to provide the tools necessary to implement a holistic method for assessing the impact of human landuse activities on catchment geomorphological and hydrological processes. The method, described in Boggs et al. (2001) involves;

1. applying landform evolution modelling and geomorphometric analysis to an undisturbed catchment,
2. developing a DEM for the conceptual ‘long-term’ state of the disturbed area and superimposing this on the undisturbed catchment (Figure 7),
3. deriving spatially distributed SIBERIA input parameters that reflect disturbed and undisturbed areas of the catchment, and
4. conducting both landform evolution simulation and geomorphometric analysis of the disturbed catchment and comparing with the results of dot point 1 above to assess both spatial and temporal impacts.

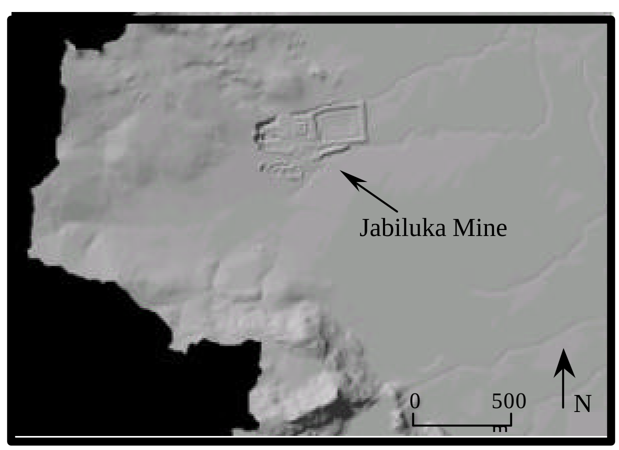

Figure 7: The Ngarradj DEM with a preliminary Jabiluka mine DEM incorporated

The application of this method within a GIS framework simplifies the implementation process and provides a more integrated approach. That is, the entire method can be implemented from within the one relatively user-friendly software environment. ArcView® being one of the most widely used desktop GIS and mapping software packages, makes the tools available to both GIS and geomorphology specialists, as well as environmental managers from both public and private sectors. Linking SIBERIA with a GIS provides many further advantages including; (1) improvements in data storage; (2) greater data manipulation and integration capabilities and; (3) more powerful analysis tools.

The elevation grids output and input by SIBERIA are composed of large amounts of data and thus require large and well-organised data-bases as well as 'user-friendly' data processing hardware and software. GIS have been designed to provide a more efficient approach for the storage and retrieval of large raster data sets (Schultz, 1993). They inherently offer data structures that reduce storage space requirements for SIBERIA data and tools that allow spatial links between datasets.

The preparation of hydrologically correct digital elevation data for input into SIBERIA is extremely important. ArcView® offers many tools for the examination and subsequent manipulation of the hydrological characteristics of a DEM. These include tools that allow the definition of stream networks and watershed boundaries and the filling of hydrological pits (artificial depressions within the DEM). Furthermore, ArcView® allows the integration of vector datasets with raster elevation data. This can be used to ensure that the DEM derived stream network correspond with accepted vector representations. Vector and raster data that describes disturbed areas can also be used to incorporate disturbed landforms within DEMs of the natural landscape. The flexibility associated with GISs for vector, raster and attribute data manipulation is a significant benefit associated with applying the impact assessment method within a GIS.

The standard tools available for the analysis of raster data within the ArcView® GIS are considerable. For example, changes in the distribution of elevation, slope, drainage networks etc can be simply calculated and statistically examined. These tools are also relatively simple to customise to provide specific tools for examining SIBERIA output. The geomorphometric measures included in the ArcEvolve extension, for example, combine functionality inherent within the ArcView® software package. The analysis of data at a variety of scales is also facilitated within a GIS. The examination of the impact of human landuse activities on landform evolution, for example, can be conducted at the local tributary, main stream or large river catchment scale to assess the relative importance of potential impacts.

4. CONCLUSIONS

ArcEvolve is an add-on program or extension for the ArcView® GIS software package that provides a GIS interface for interacting with the SIBERIA landform evolution model and examining the model output using geomorphometric measures. The extension includes the tools necessary to perform a GIS-based assessment of the impact of human landuse activities on catchment geomorphological and hydrological processes. Linking the SIBERIA model with a GIS provides many advantages including a fully integrated environment for the preparation, modelling and analysis of landform evolution, improved data storage and management, greater data manipulation capabilities and more powerful tools for the final analysis of the impact of landuse activities on landform evolution. The extension is currently a prototype that will be tested through the assessment of the impact of the ERA Jabiluka Mine, located in the Northern Territory of Australia, on the surrounding Ngarradj catchment.

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