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Application of landform evolution modelling to the Nabarlek minesite

JBC Lowry, DR Moliere, GS Boggs & KG Evans

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1 Introduction

The impact of mining activities on complex and relatively poorly understood environments represents a significant issue facing decision-makers in northern Australia (Boggs et al 2001). The Cooper Creek catchment, a major right-bank tributary of the East Alligator River, will be the first catchment to be affected should any impact occur as a result of possible design flaws in the rehabilitation of Nabarlek mine. The mine was rehabilitated in 1995 under the requirements of Northern Territory Uranium Mining Act 1979 and other legislation (Waggitt 1998). There is a need to assess the impact of the rehabilitated mine on the Cooper Creek catchment before the return of the site to the Traditional Owners. An important part of this assessment is to predict the surface stability of the landform using erosion and landform evolution modelling techniques.

It is considered that landform evolution modelling of the stability of post-mining rehabilitated landform designs was first conducted by Willgoose and Riley (1993) using the SIBERIA landform evolution model (Willgoose et al 1989). Since 1993, the model has been used principally to investigate surface stability of post-mining rehabilitated landforms or small catchment areas (ie Willgoose and Riley 1998; Evans et al 1998; Hancock et al 2000, 2002; Moliere et al 2002). Boggs et al (2000, 2001) applied the landform evolution model, SIBERIA, to a medium scale, mining affected catchment area by linking the ArcView 3.2® desktop GIS software package with the SIBERIA model. This technique provided a spatial approach to assessing the impact of mining activities on the long-term landform evolution of a catchment. A product of this approach was the development of an extension known as ArcEvolve, which links SIBERIA with ArcView 3.2 (Boggs et al 2001).

In this study, the ArcEvolve software was applied to the catchment areas affected by the Nabarlek mine site. The aims of this study are to:

(1) assess the application of ArcEvolve to a small mine-impacted catchment,

(2) predict the surface stability of the catchment areas affected by the Nabarlek mine and determine possible future impacts; and

(3) produce a detailed description of the processes and methods for the future application of ArcEvolve to medium-scale catchment areas.

The third point is particularly important for the future application of the model by the Supervising Scientist Division (SSD) to the rehabilitation design of the Energy Resources of Australia Ranger mine (ERARM) for impact assessment.

1.1 Study site

The rehabilitated Nabarlek uranium mine is situated in western Arnhem Land about 270km due east of Darwin (fig 1) in the upper catchment area of Cooper Creek. Cooper Creek is a major tributary of the East Alligator River and as such forms part of the Alligator Rivers

Region, an area of high international significance in both natural and cultural values (Environment Australia 2002). Located in the monsoon tropics climatic zone, the region experiences a distinct Wet season from October to April, and a Dry season for the remainder of the year. Stream flow in the Cooper Creek catchment area, as a consequence, is highly seasonal. The average annual rainfall for the region is approximately 1410 mm (Bureau of Meteorology pers comm. 2001).

The Cooper Creek channel flows in a northerly direction from the Arnhem Land sandstone plateau to within approximately 1 km to the east of Nabarlek (fig 1). Grabham (2000) identified three left bank tributaries that are affected by mining at Nabarlek – Buffalo Creek, Kadjirrikamarnda Creek and West Cooper Creek (fig 2). All three creeks lie predominantly within the lowland plains of the upper reaches of the Cooper Creek catchment. These three catchments cover an area of 476, 481 and 339 Ha respectively, of which 69, 22 and 13 Ha are disturbed (Garland et al 2003). Disturbed areas incorporated in the modelling in this study include the evaporation pond, mine pit, waste rock dump and the 1.6 km-long airstrip (fig 2).

1.2 Site history

The Nabarlek orebody was discovered in 1970 by Queensland Mines Limited (QML) during an aerial spectrometer and magnetometer survey. The uranium deposit was excavated by QML between April and October 1979 by removal of 606 700 tonnes of ore containing approximately 12 000 tonnes of U_3O_8 at an average grade of about 2% (Riley 1995). Processing of the ore was completed in 1989.

Decommissioning was undertaken through the Wet season of 1994–95 and the site rehabilitated in 1995 (Prendergast et al 1999). This included: removing all surface structures (such as evaporation ponds and plant equipment); returning tailings from the processing plant to the open pit; covering the area with waste rock mulch; deep ripping, and; seeding the area with shrub and tree species (Riley 1995, Waggitt 1998).

A site inspection in 1999 (Evans et al 2001) found severe gullying along roadways, while buildings and other infrastructure were in a poor state of repair.

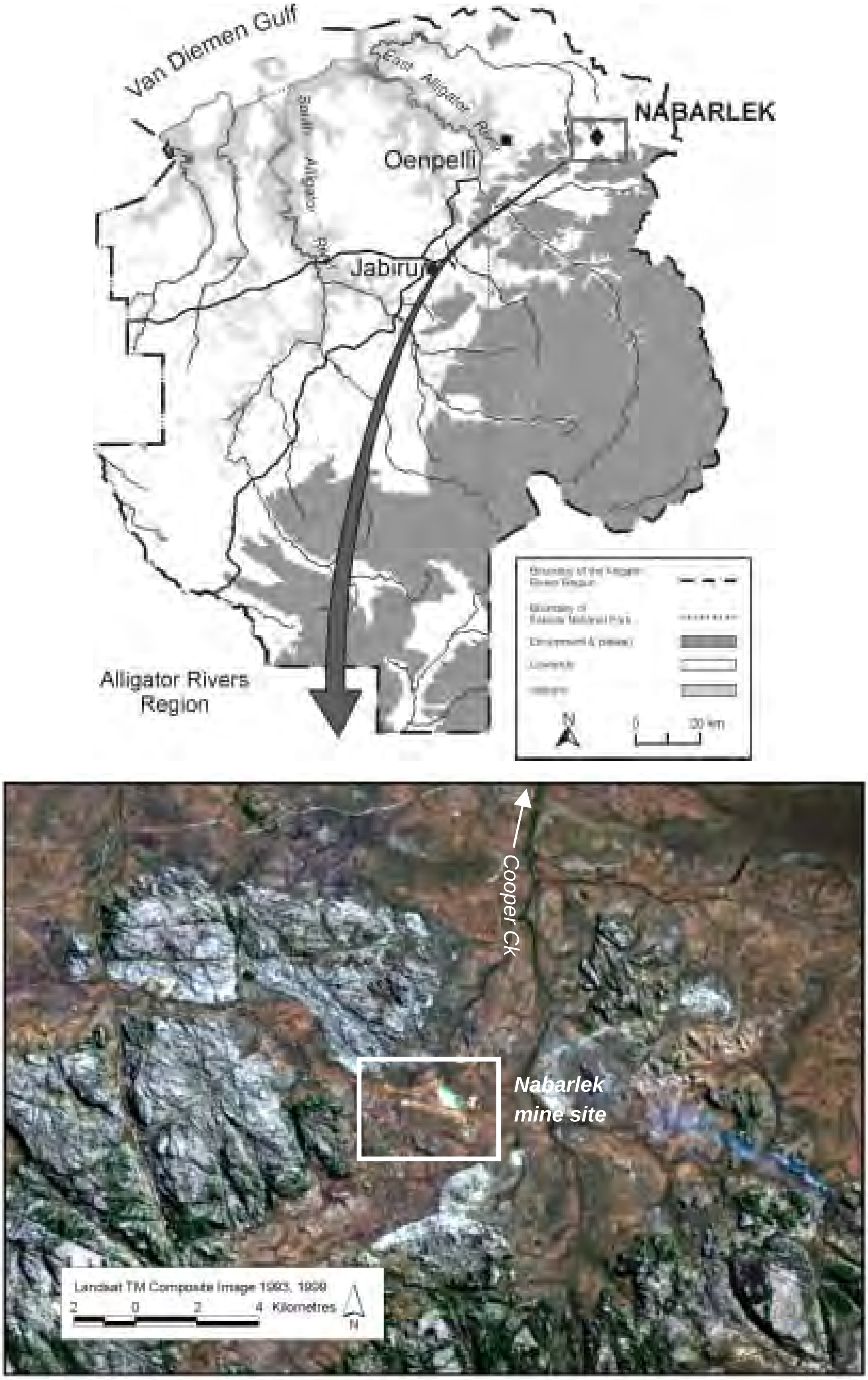


Figure 1 Location of Nabarlek in the Alligator Rivers Region (Top). Stream system and sandstone outliers surrounding Nabarlek are also shown (Bottom).

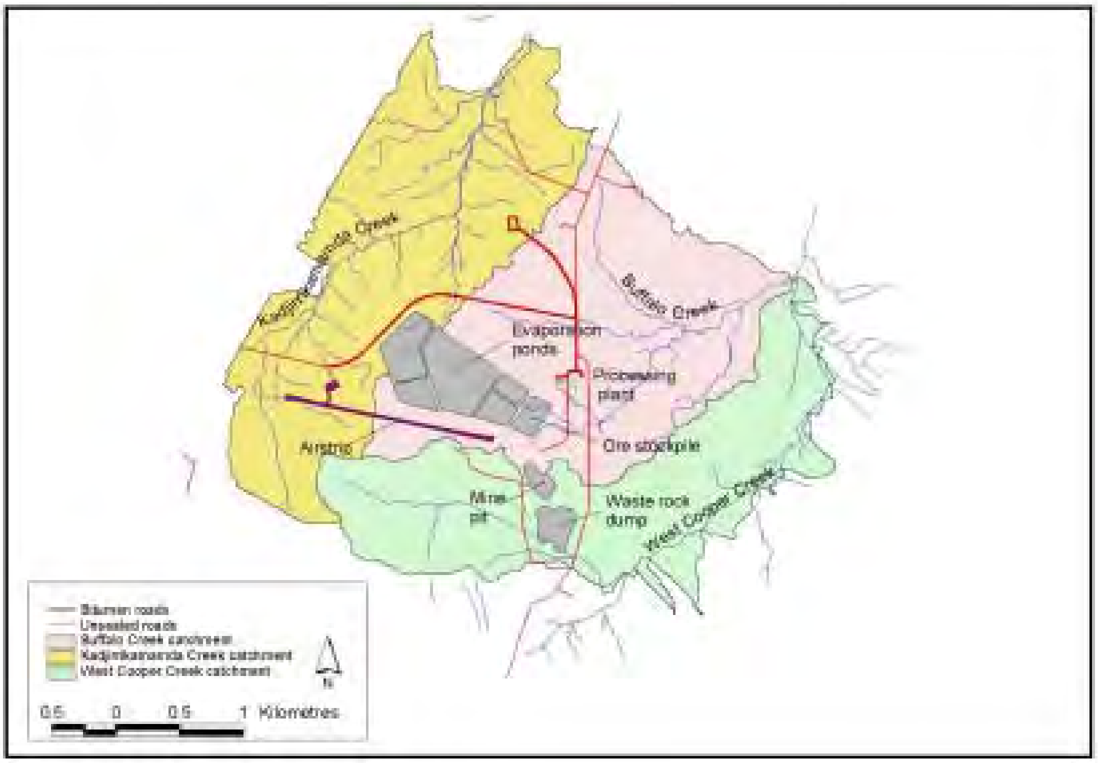


Figure 2 Nabarlek mine site features and the affected streams (Top). Aerial photograph of Nabarlek taken January 1999 (Bottom).

2 SIBERIA model

The SIBERIA landform evolution model is a sophisticated three-dimensional topographic evolution model. SIBERIA models long-term changes in elevation with time from the average effect of mass transport processes, such as tectonic uplift, fluvial erosion, creep, rainsplash and landsliding. The model describes how a catchment will look, on average, at a given time.

SIBERIA is also a complex model that requires extensive parameterisation (Willgoose et al 1991). Parameterisation of the model generally requires the use of separate hydrology and sediment transport models to derive a discharge/area relationship, long-term sediment loss and a sediment transport rate (fig 3).

To date, the model has been used to investigate post-mining rehabilitated landform design at the ERARM (ie Willgoose & Riley 1998; Evans et al 1998, Moliere et al 2002) and Energy Resources of Australia Jabiluka mine (ERAJM) (Boggs et al 2000, 2001). These previous studies have used observed data (rainfall, runoff and sediment loss) collected at field sites, located on the landform or within the catchment to be modelled, to parameterise SIBERIA. It is important to note that in this study, there were no hydrology and sediment loss data collected at field sites within the Nabarlek region. Therefore, there were no SIBERIA parameter values derived for the various surface conditions within the Nabarlek catchment area modelled. Instead, parameter values derived in the above previous studies (Evans et al 1998, Boggs et al 2001; Moliere et al 2002) were used to represent the various surface conditions within the Nabarlek catchment area.

The following section provides a brief outline of the parameter derivation process and defines the parameters that are required as input into the model.

2.1 Parameter derivation

SIBERIA predicts the long-term average change in elevation of a point by predicting the volume of sediment lost from and added to a node on a DEM using the fluvial sediment transport equation:

$$q_s = \beta_1 q^{m_1} S^{n_1} \quad (1)$$

where: q_s = sediment transport rate (m^3 y^{-1}), S = slope (m/m), β_1 = sediment transport rate coefficient; and m_1 and n_1 are fitted parameters.

q = discharge or peak discharge and is dependent on drainage area (A) as follows (Leopold et al 1964):

$$q = \beta_3 A^{m_3} \quad (2)$$

To run the SIBERIA model for a field site it is necessary to derive parameter values for β_1, m_1, n_1 (eqn 1) and β_3, m_3 (eqn 2). Parameter values for equations (1) and (2) are derived by:

- extending the observed runoff record collected at the field sites by calibrating a rainfall-runoff model;
- fitting parameters to a sediment transport equation using sediment concentration and runoff data collected from field sites (n_1, m_1); and
- using the results of steps 1 and 2 above to derive long-term average SIBERIA model parameter values for the landform being modelled (β_1, β_3, m_3).

Figure 3 shows a flow diagram of the parameter derivation process. A detailed description of the process is given in Willgoose & Riley (1998) and Evans et al (1998).

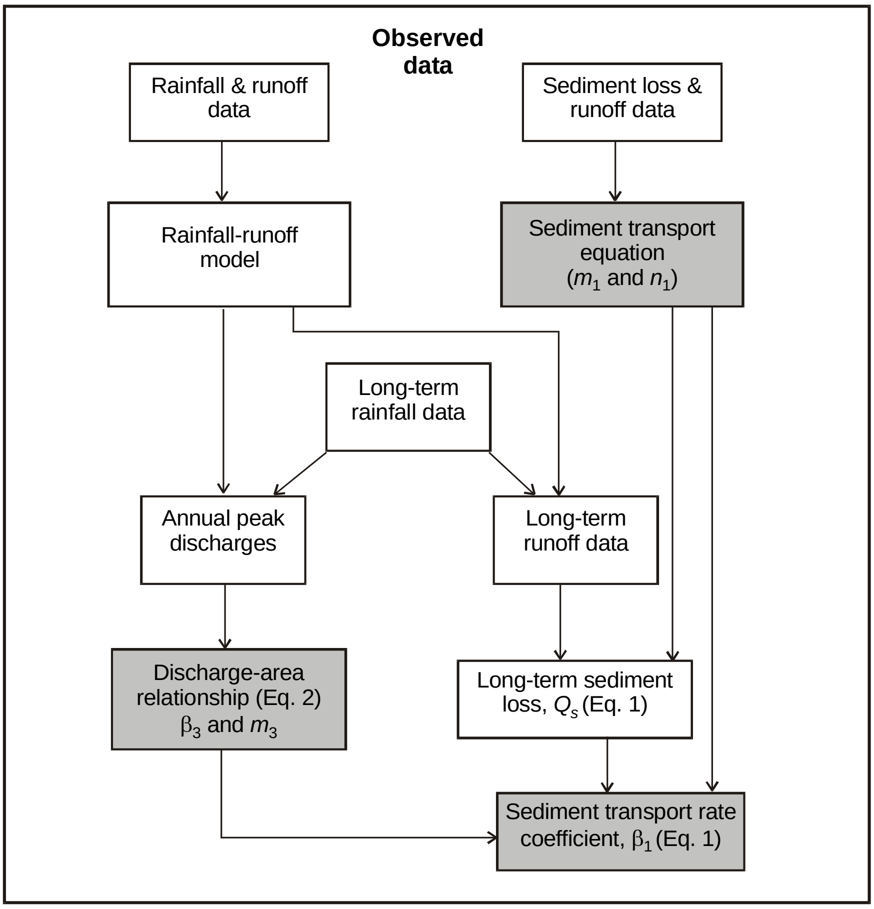


Figure 3 Flow diagram representing the SIBERIA input parameter derivation process. The shaded boxes indicate parameters used as input into the model.

2.2 SIBERIA input parameter values

As discussed above, the SIBERIA input parameter values are dependent on the surface condition of the catchment or region to be modelled. The parameter values describe the long-term erosion and hydrological characteristics of the area. There are several disturbed regions within the Nabarlek catchment area, such as the evaporation pond, mine pit, waste rock dump and airstrip (fig 2). These regions have contrasting surface conditions to the surrounding landscape, and as a result, these regions will have very different input parameter values to that of the natural landscape. A description of the surface condition of each of the regions is given below.

2.2.1 Natural surrounding landscape

The natural soil in the region, which originate from weathering of the local geology (QML 1979), is comprised of three main types – dolerite derived sandy soils, schist derived soils and soils of moderate clay content in the Buffalo Creek catchment (Grabham 2000). The natural vegetation is dominated by *Eucalyptus* and *Acacia* (Storey et al 1976). *Sorghum* sp. and *Acacia* spp. dominate the understorey (Riley 1995).

In this study, we have assumed that the surface condition of the natural landscape at Nabarlek is similar to that of the Koolpinyah Surface. The Koolpinyah Surface is a peneplain, and has very low erosion rates. The runoff and erosion characteristics of this surface, defined by a set of SIBERIA input parameter values (table 1), were derived in Moliere et al (2002). Moliere et al (2002) assumed that these parameter values were representative of the landscape at Ranger before the commencement of mining operations.

2.2.2 Disturbed/rehabilitated area

The overall surface of disturbed areas, such as the evaporation ponds, the mine pit and the waste rock dump were left covered with run-of-mine waste rock. The waste rock consists mainly of schistose material, which had been observed to weather rapidly on the waste rock dump (Waggitt 1998). The schistose waste rock consists of quartz-mica, chlorite-mica and quartz-chlorite schist (Riley, 1995). Particles less than 2mm in diameter form 50% of the soil and weather rapidly to form clay, fine gravels and micaceous sand (Riley, 1994). There are many large rocks still present on the rehabilitated surface, in some areas 50% of the surface covered by rocks >100mm in diameter. The surface of the evaporation ponds were also covered with soil from the stockpiles and ripped to assist rainfall infiltration.

The aerial photograph of Nabarlek (fig 2) shows that almost 50% of the mine site area has vastly different vegetation cover to that of the surrounding natural landscape. The rehabilitated evaporation pond area supports very little woodland community and is dominated by grass cover (fig 2). The surface of the mine pit and the waste rock dump supports trees, but lacks the understorey which exists on the surrounding landscape (Prendergast et al 1999). The airstrip itself and the surface immediately surrounding the airstrip are devoid of vegetation (fig 2).

Evaporation ponds

In this study, we have assumed that the surface condition of the evaporation pond is similar to that of a vegetated, ripped field site on the Ranger waste rock dump. The site at Ranger was top-soiled and surface ripped and was vegetated with low shrubs and grasses which provided approximately 90% cover (Evans et al 1998). The average slope of the site at Ranger is approximately 1% (Evans et al 1998), similar to that of the evaporation pond area (Grabham 2000). The SIBERIA parameter values for this site (table 1) were derived by Evans et al (1998).

Mine pit and waste rock dump

We have assumed that the surface condition of these two areas are most similar to that of a field site on the waste rock dump at Ranger. This site at Ranger was located on a batter slope of the waste rock dump and was covered with an armour of coarse material with little vegetation cover. The SIBERIA input parameter values fitted for the site at Ranger (table 1) (Moliere et al 2002) are considered to provide a conservative estimate (in terms of impact assessment) of the erosion likely to take place in this region of Nabarlek. The waste rock material on the mine pit and waste rock dump area at Nabarlek has a much higher vegetation cover than that of the field site at Ranger.

Airstrip

The airstrip consists of a bitumen landing surface surrounded by bare soil (fig 2). The bitument landing strip is assumed to be an impermeable surface and therefore was not modelled. Only the areas of bare soil surrounding the landing surface were modelled in this study. We have assumed that the surface condition of the areas of bare soil is most similar to the roads constructed on the ERAJM. The roads at ERAJM consisted of bare, compacted soil with no vegetation and SIBERIA input parameters for this surface condition were derived by Boggs (2003) (table 1).

Table 1 The SIBERIA parameter values for each region of the Nabarlek catchment area

Region	Comparable site	SIBERIA parameter				
		m_1	n_1	β_3	m_3	$*\beta_1$
Natural, surrounding landscape	Koolpinyah surface (Moliere et al 2002)	1.12	0.69	0.00017	0.81	3.5
Evaporation pond	Vegetated, ripped surface (Evans et al 1998)	1.59	0.69	0.000006	0.90	1100
Mine pit and waste rock dump	Ranger waste rock dump (Moliere et al 2002)	2.52	0.69	0.00016	0.81	14618
Airstrip (bare soil)	Jabiluka roads (Boggs 2003)	2.24	0.69	0.0006	0.59	13683

* β_1 values were revised in this study to correspond with the DEM resolution (25.31 m grid size)

3 ArcEvolve – a SIBERIA–GIS interface

The SIBERIA model is a difficult program to operate, particularly in terms of the data entry and extraction process. Boggs (2003) derived a user-friendly interface, ArcEvolve, for the SIBERIA model within a desktop GIS. Boggs (2003) used a 'tight coupling' approach to integrate SIBERIA with ArcView 3.2®, which means that the file or information sharing between the GIS and modelling components is transparent to the end user (Loague & Corwin, 1998).

The SIBERIA model uses what is known as a 'restart' file as its standard input and output. Restart files have a plain text format and contain data on the DEM and up to 80 individual parameters which relate to the running of the model and the erosion, hydrology, channel and tectonic characteristics of the landform. It is important to note that at present, the ArcEvolve extension only interacts with the plain text format restart file. The ArcEvolve extension provides users with the option of importing 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.

SIBERIA parameters are stored by the GIS within tables, where each record in the table relates to 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 and edit 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 catchment area, including the location of the catchment outlet(s). 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. The different 'regions' within the region file may represent different areas of disturbance, such as the evaporation ponds, airstrip, waste rock dump and mine pit. 'Region files' are identical in format to boundary files being composed of the x and y coordinates of the boundary of the region. The location and area of these regions 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.

3.1 Software requirements

ArcEvolve 1.3 has been developed as an extension to the ArcView 3.2 GIS software package. It is important to note that ArcEvolve does not actually replace the SIBERIA program, but instead provides a front end to the program through a user-friendly GIS interface. It is therefore necessary to have a copy of the latest version of the SIBERIA software program (version 8.15) in addition to a copy of ArcEvolve 1.3 installed. *Importantly, earlier versions of SIBERIA (ie v8.06) will not run reliably with ArcEvolve 1.3.*

The steps for installing the ArcEvolve extension are described in Appendix 1. It is important to note that for the 'tight-coupling' between the two programs to occur, the SIBERIA program must be installed on the following path:

C:\program files\landtech\eams\SIBERIA815.exe

As an ArcView 3 series extension, ArcEvolve has been written using the Avenue programming code. ArcEvolve was developed with the intention of being used in conjunction with the following ArcView 3 series extensions: ArcView Spatial Analyst®, ArcView 3D Analyst® and the Hydrological Modeller. The first two extensions are required to enable the manipulation and querying of grid themes, and are marketed and sold as individual products by ESRI. The Hydrological Modeller extension is supplied with the Spatial Analyst extension and is used for ensuring that datasets are hydrologically correct. At present, ArcEvolve is not supported by the ArcGIS range of products.

3.2 Hardware requirements

The hardware requirements of ArcEvolve are very closely linked to the software requirements, in that the computer selected must be able to run ArcView with the Spatial Analyst and 3D Analyst extensions active, and also run the SIBERIA program. In order to be able to run these programs successfully, it is recommended that a workstation with, at the minimum, a Pentium 4 1.5Ghz processor and 512 MB RAM be employed. It is also recommended that at least 1 GB of free hard disk space be available for the creation of output files. It should be noted that when running some simulations (ie for 2500 years) it may take several hours for SIBERIA to process the model and produce outputs. For convenience, the workstation on which the model is running should be able to run several programs concurrently.

3.3 Managing model inputs and outputs

ArcEvolve enables users to specify the path and directory to which the data are to be saved. All model input and output files should be created and stored in a specific directory on the local drive of the machine being used for the modelling. At the conclusion of the modelling process, metadata records should either be created or updated. The results of the modelling process should then be transferred into SSD Explorer, along with the corresponding meta data record.

It is important to note that ArcInfo Grid datasets are composed of two directories - one bearing the dataset name and the other an ‘Info’ directory. SSD Explorer currently has a number of limitations in handling datasets which require links to be maintained between and within two or more directories. In order to bring the directories into SSD Explorer, the “Control-Shift-Q” command could be used to copy entire directories. Note that when the grids need to be used or viewed again, both directories need to be copied out to the same working area.

Alternately, when the SIBERIA outputs have been completed (and displayed in ArcEvolve), they may be exported as an ASCII Raster dataset. This will create a single ASCII file containing the parameters of the grid dataset. As a single file, it is easier to import and manage in the SSD Explorer environment than multiple grid directories.

4 Landform evolution modelling using ArcEvolve

The steps developed for the application of landform evolution modelling using ArcEvolve at Nabarlek are summarised in figure 4, and are described in more detail in the following sections.

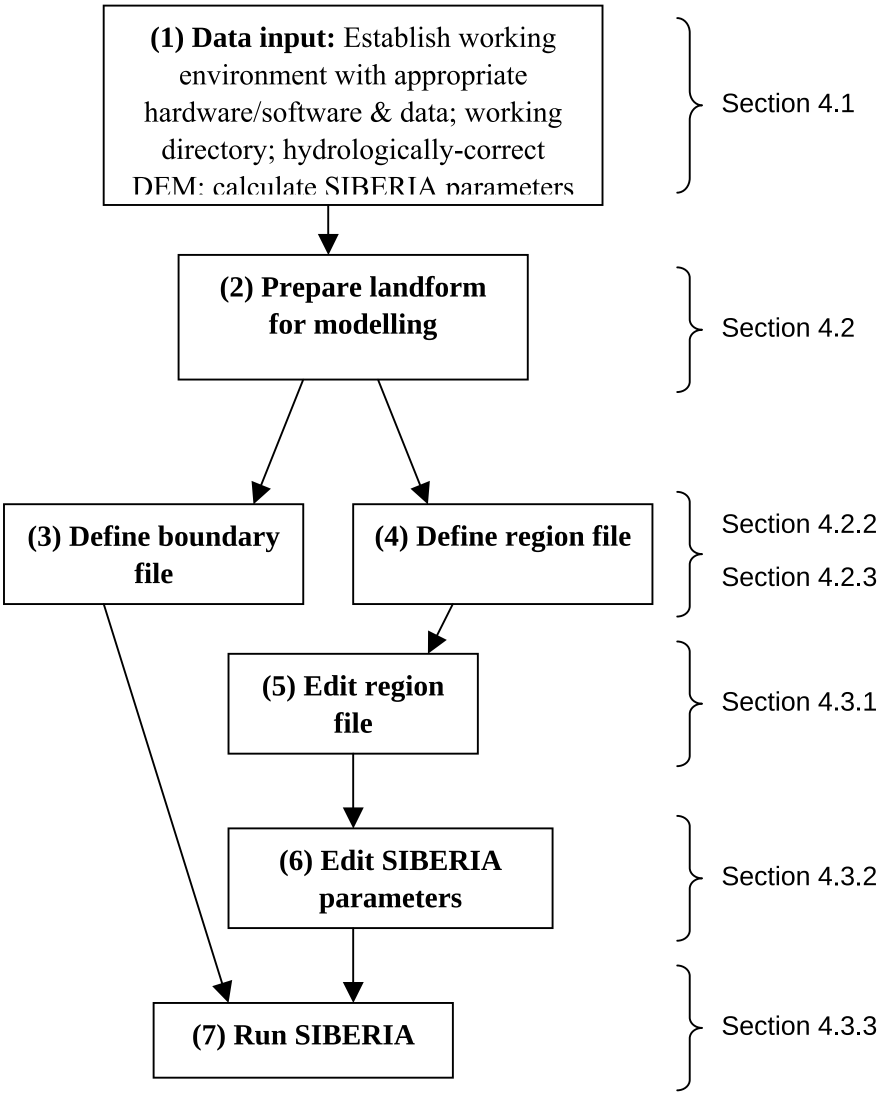


Figure 4 Summary of landform evolution modelling steps at Nabarlek

4.1 Data input - DEM

Digital elevation models (DEMs) are central to the modelling concepts incorporated into SIBERIA, and by extension, ArcEvolve. DEMs are required as the initial input (from which features such as boundary files are generated) and are the product of the modelling process. A DEM may be produced in a variety of ways, from a number of sources, and in a range of formats. Consideration should be given to the following in the selection and/or creation of a DEM for use with ArcEvolve:

1. The DEM should be hydrologically correct. That is, the DEM should be built in a manner to ensure that streams flow in the correct direction (eg not uphill!) and that sinks

and catchment outlets occur in the right place. The Hydrological Modeller extension in ArcView 3.2® was used to verify the hydrological integrity of the DEM of the Nabarlek catchment area.

2. A significant limitation of the current version of SIBERIA is its' inability to handle grid arrays greater than 250 columns by 250 rows. Grids (or DEMs) with arrays in excess of this may need to be resampled or aggregated to meet this requirement. An avenue script which may be used to aggregate grids is listed in Appendix 2.

In this study, a DEM of the Nabarlek area was generated from 2-metre contours derived from 1:15,000 aerial photography, to produce a grid with an array of 182 columns and 190 rows, enabling the three mine impacted catchments (Buffalo, West Cooper, and Kadjirrikamamda creeks) to be modelled.

While ArcEvolve (through the ArcView desktop environment) and SIBERIA are able to read DEMs in a variety of formats, it is recommended that they be created and maintained in the ArcInfo Grid format.

A fundamental component of the landform evolution modelling process is the grid dataset representing the disturbed areas on the landform, such as the airstrip, evaporation ponds, the mine pit and the waste rock dump. While these features may be created as vectors, for example through digitising disturbed areas indentified on aerial photographs, in order for the disturbed area to be integrated within the DEM representing the landform and used in the modelling process, they need to be either converted to, or created as, grid themes.

Ancillary data

The principal ancillary dataset which may be required for landform modelling is one representing the drainage characteristics of the landform. This dataset is required to help define the catchment outlet in the boundary file (see Section 4.2.2). A drainage dataset for a landform can be generated from a DEM using the Hydrological Modeller extension in ArcView. In this study, drainage data generated by Garland (2002) was used.

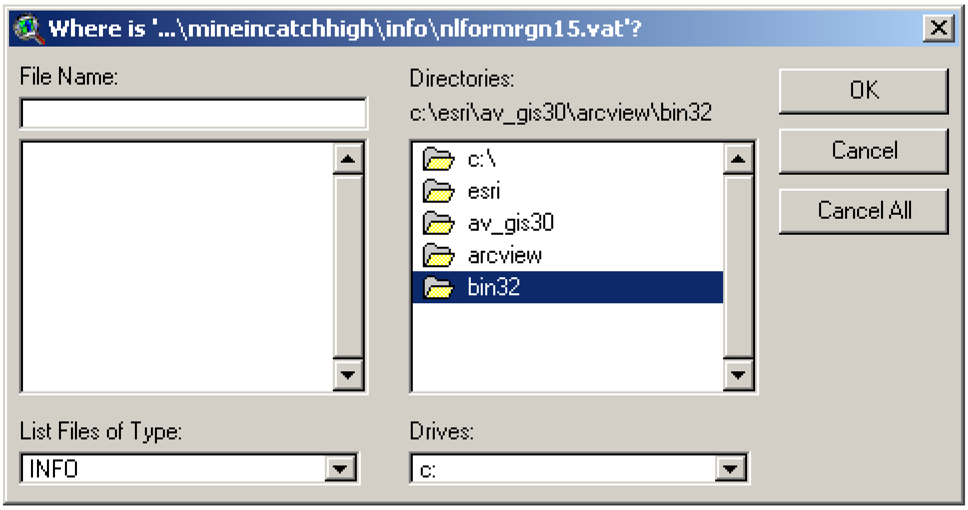
4.2 Preparation of the landform to be modelled

The following section describes the step-by-step process to create and define the catchment boundary and the disturbed areas within the catchment area. This process must be completed before running the SIBERIA model on the landform. The following description also assumes the user has a basic knowledge of ArcView.

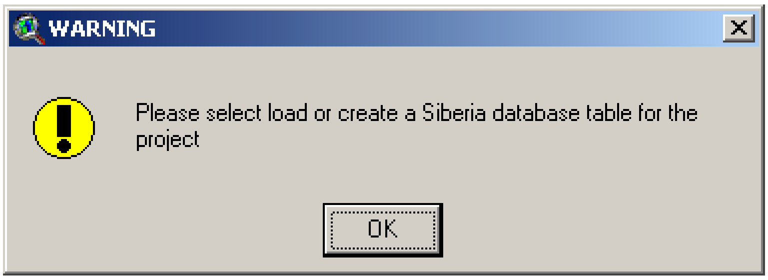
4.2.1 Creating the SIBERIA database in ArcView

A new project was created in ArcView 3.2 with extensions ArcEvolve 1.3, Spatial Analyst and Hydrological Modeller selected from the File/Extension menu (Appendix 1).

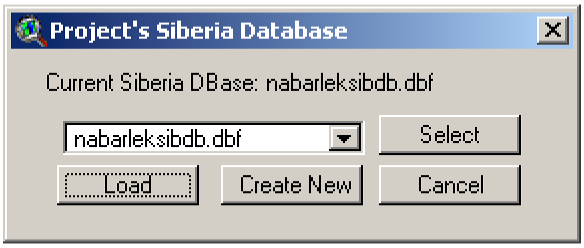
(Note: when creating a new project, or loading an existing project using ArcEvolve, a series of dialog boxes querying the location of various files will appear. Press 'Cancel All'.)



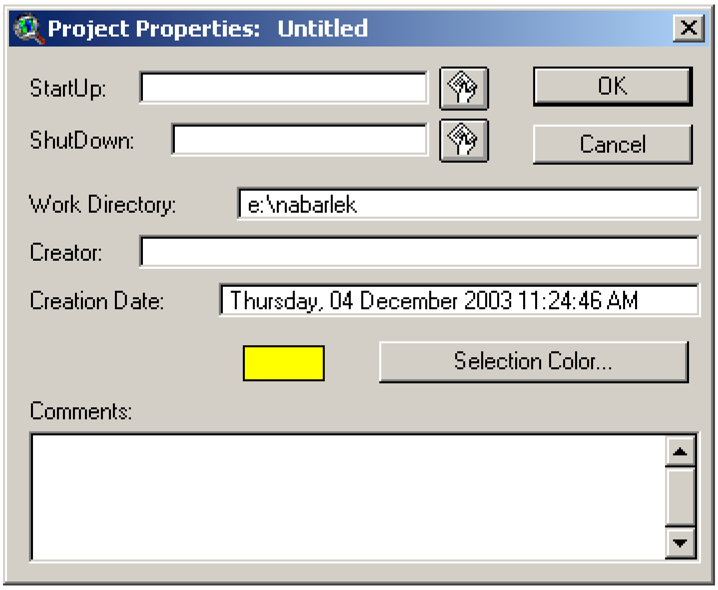
A prompt appears, asking for a SIBERIA database to be either created or selected.



A new SIBERIA database was then created within the following dialog box. It was important to create a directory on the local drive in which to store all relevant files, including outputs, associated with the modelling process. The new SIBERIA database was saved into this directory.



Hint: It is possible to set a working directory in ArcView, which minimises the amount of navigation required when prompted where files are to be saved/stored. This can be done from the Properties menu in the Project document. The default directory for files is c:\temp.

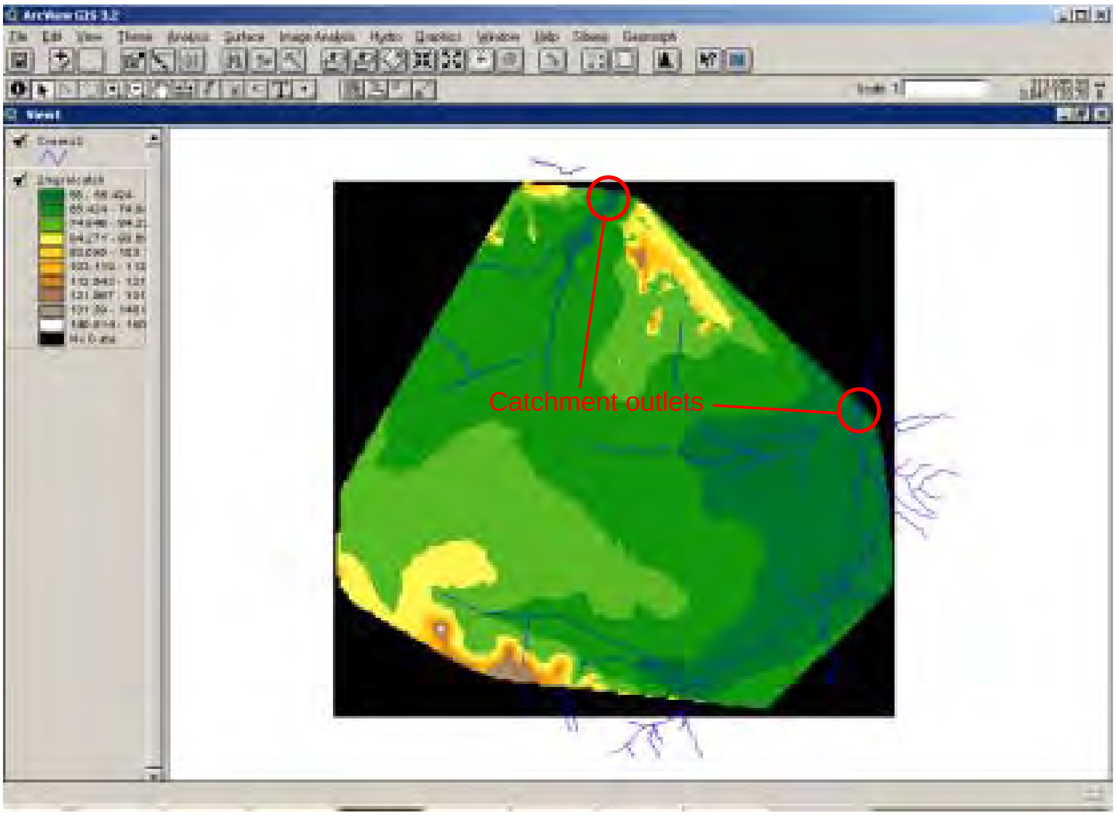


4.2.2 Defining the catchment boundary file

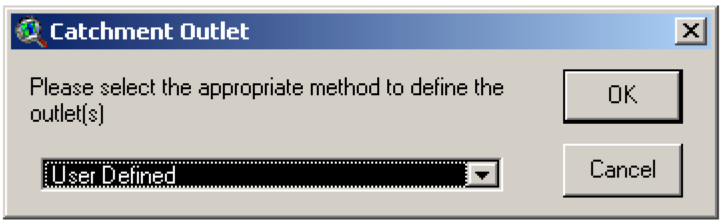
The area within the catchment boundary represents the landform to be modelled. To create the boundary file in ArcEvolve, the catchment outlet on the landform needs to be identified.

The DEM of the Nabarlek catchment area was loaded into ArcView. As discussed above (Section 4.1), it was important that the DEM (a) was in an ArcInfo grid format, (b) was hydrologically correct, and (c) consisted of an array size less than 250 cells by 250 cells. In this study, a DEM with an array of 182 cells by 190 cells was used. The size of each grid cell modelled was 25.31 m^2.

A dataset representing the hydrological features of the landform was also added to the view. The overlay of the two datasets (the DEM and the flow lines) was used to identify the catchment outlet(s) (shown below). In this study, the dataset representing the flow lines was a vector coverage of drainage features generated from the DEM of the landform using the Hydrological Modeller extension in ArcView. (It should be noted that if an independently generated dataset is used (one not derived from the DEM of the actual landform being modelled), it should be of an appropriate scale that is compatible with the landform. For example, the hydrological features compiled to a scale of 1:250 000 should not be used on a DEM compiled to a scale of 1:25 000.)



To identify the catchment outlet on this view, the 'Create boundary grid' option was selected within the SIBERIA menu (ensuring the DEM is the active theme). Within the subsequent dialog box, the method used to define the catchment outlet was selected ('user defined').



The outlet is defined as the point at which the drainage line leaves the catchment (as shown above). This point was selected by clicking the mouse button over the outlet (the zoom magnifying tools were required to enhance the area and more accurately select this point). In this study, there were two catchment outlets identified for the Nabarlek area.

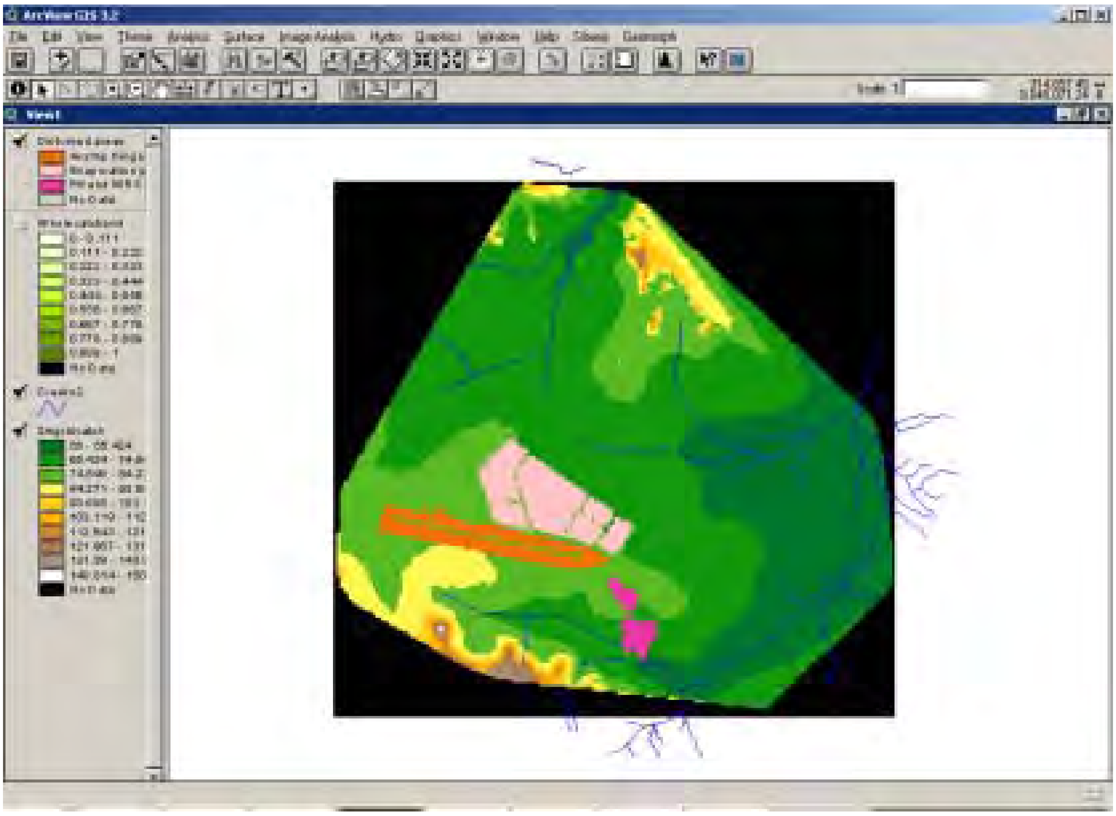
The identification of the catchment outlets automatically generates the boundary grid file, once 'OK' had been clicked. The resultant boundary file was saved to the same work directory established above (Section 4.2.1).

4.2.3 Defining the region file

The region file defines the surface conditions within the study area. In this study, two region files were generated, the first representing the entire catchment in an undisturbed (natural) state, and the second in a disturbed (eg mine-impacted) state. The latter file contained four separate regions that defined each of the different surface conditions within the Nabarlek catchment area (table 1). The steps used to generate the two region files are decribed below.

Disturbed region file

A raster (grid) dataset was created to represent the disturbed areas on the landform (airstrip, evaporation ponds and the mine pit and waste rock dump area). Existing vector datasets of the disturbed areas (digitised from aerial photography) were converted to grid/raster format using the 'Convert to Grid' option under the *Theme* menu. The resultant raster dataset was saved to the same work directory established above (Section 4.2.1). This dataset was then added to the view overlaying the DEM.



It was important to ensure that the extent of the newly created raster dataset matched that of the boundary file created earlier (Section 4.2.2). This process is briefly described as follows:

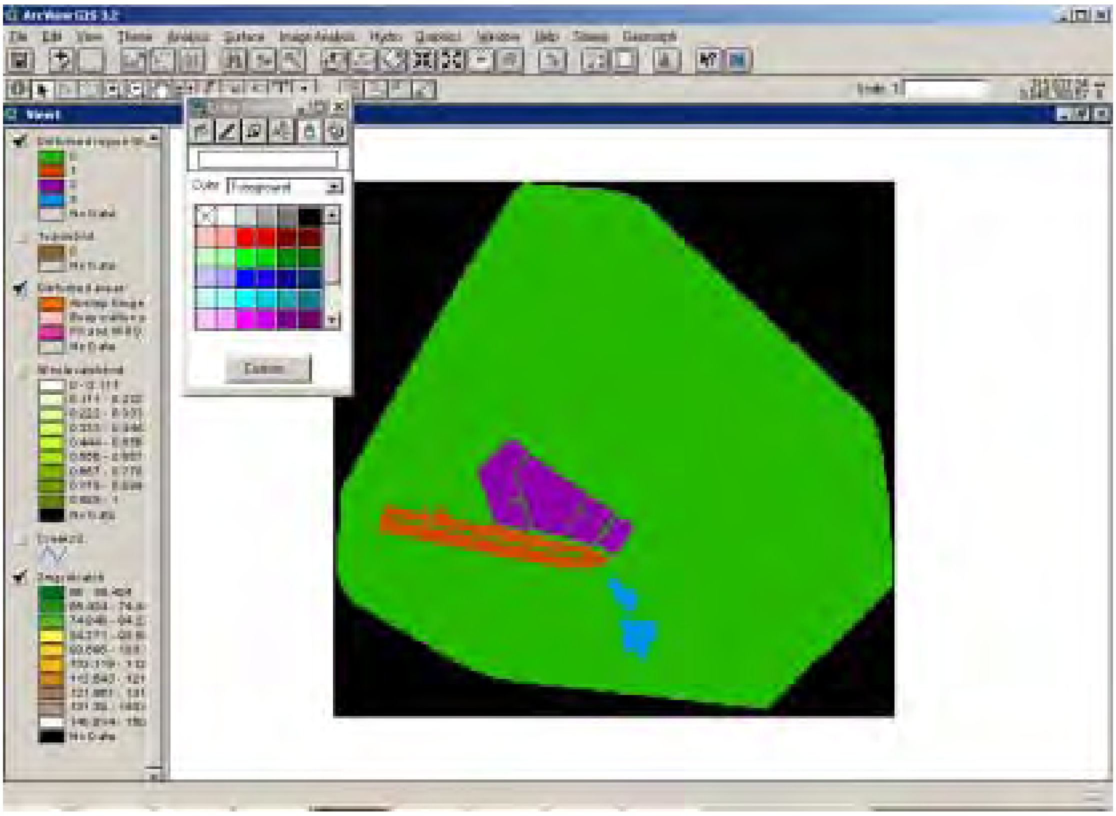
- The boundary file was amalgamated with the disturbed areas. This was done by first, reclassifying the boundary file to a single value (refer to Appendix 3), then using the 'Map Calculator' option from the *Analysis* menu. The syntax code used was:

  ([disturbedgrid].isnull = 0.asgrid).con([disturbedgrid],[1valueboundaryfile])

  which produced a map calculation grid composed of values 0,1,2,3 and 'No data'.

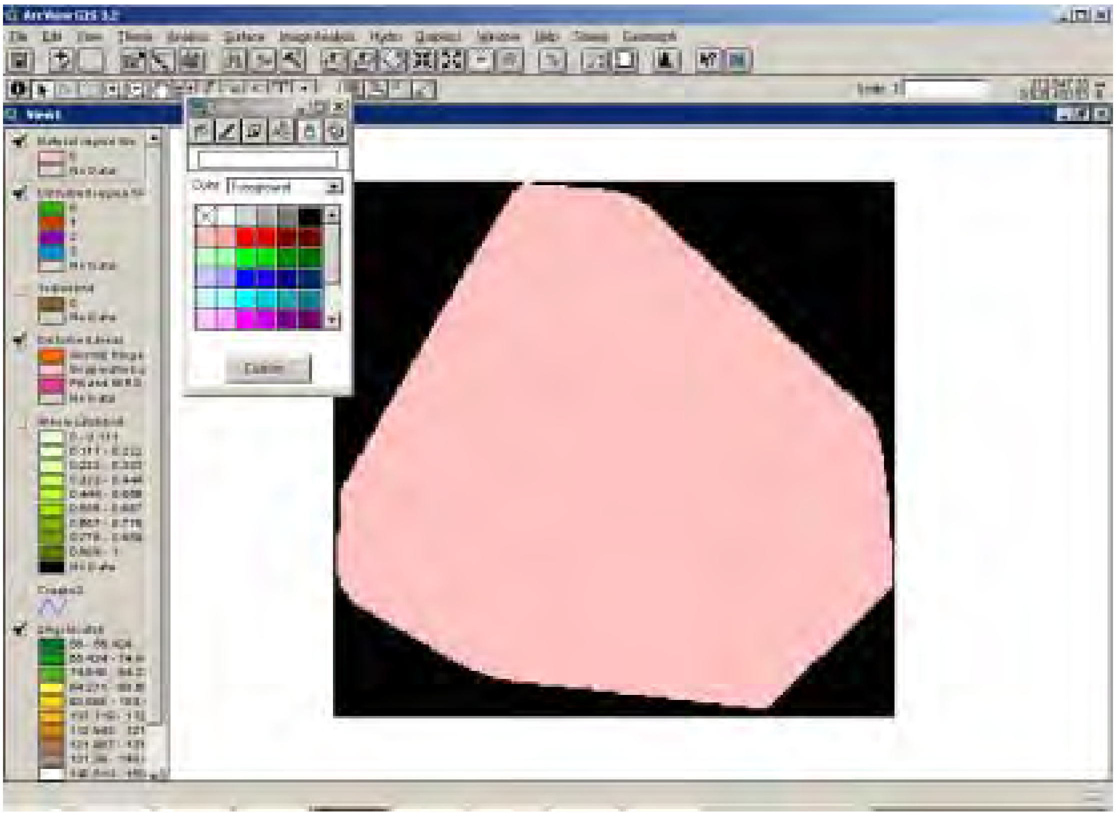
- Values 1 - 3 represent the three disturbed surface conditions within the catchment (table 1). Value 0 represents the remaining area within the boundary file (the natural surface). 'No data' represents the area outside of the boundary file, which is not part of the catchment being modelled (indicated by the black area in the figure below).

- The map calculation was saved as a grid using the 'Convert to Grid' option under the *Theme* menu, and saved in the same working directory as the earlier files. The grid produced through this process is the 'disturbed' region file. (In order to minimise the number of files in use, the map calculation grid was deleted from the view using the 'Delete themes' option from the *Edit* menu.)



Undisturbed region file

To create the 'undisturbed' (natural surface condition) region file, a copy of the 'disturbed' region file was made using the 'Convert to Grid' option under the *Theme* menu. This was then reclassified (using the 'Reclassify' option under the *Analysis* menu) to produce a new region containing only the 'natural' regions, and saved to the project working directory. The process employed in reclassifying the region file to a single region was the same as used in the generation of a single-value boundary file, described in Appendix 3.



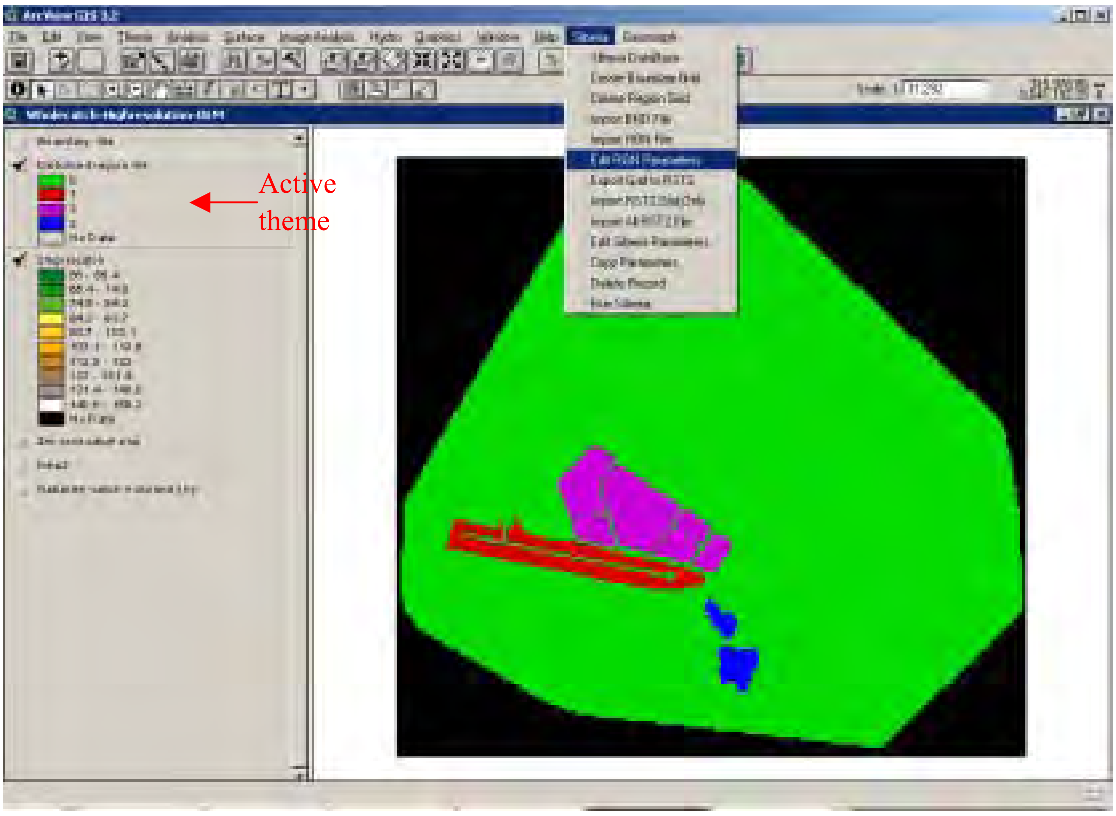
4.3 Running SIBERIA

Before SIBERIA can be run through ArcEvolve, it is necessary to input the SIBERIA parameter values into the model. The parameters which describe the long-term erosion and hydrological characteristics of the various surface conditions (table 1) are assigned to the region file (created in Section 4.2.3). The more general SIBERIA parameter values, which describe the entire landform being modelled, including the simulation run time and outputs, are given in the SIBERIA database (created in Section 4.2.1). A description of all the parameters used in the SIBERIA model is given in Willgoose (1992).

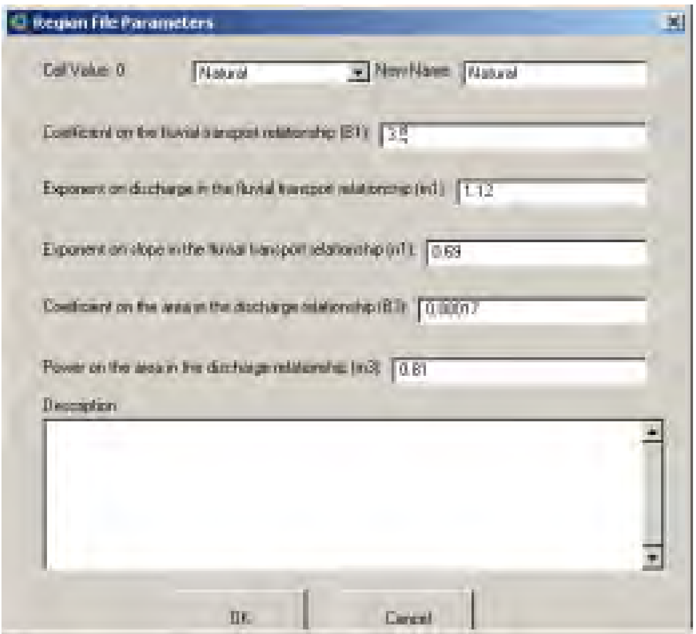
4.3.1 Region file parameters

In this step, the parameter values for each surface condition within the catchment area to be modelled are input into the model. As mentioned above, it is assumed that there are four separate surface conditions within the Nabarlek mine-impacted catchment area, each with a set of SIBERIA parameter values which describe the long-term erosion and hydrological characteristics of the surface (table 1).

To input these parameter values into the model, the item 'Edit RGN parameters' from the *SIBERIA* menu was selected. It is important to make sure the region file is the active theme before selecting this menu item (see below).

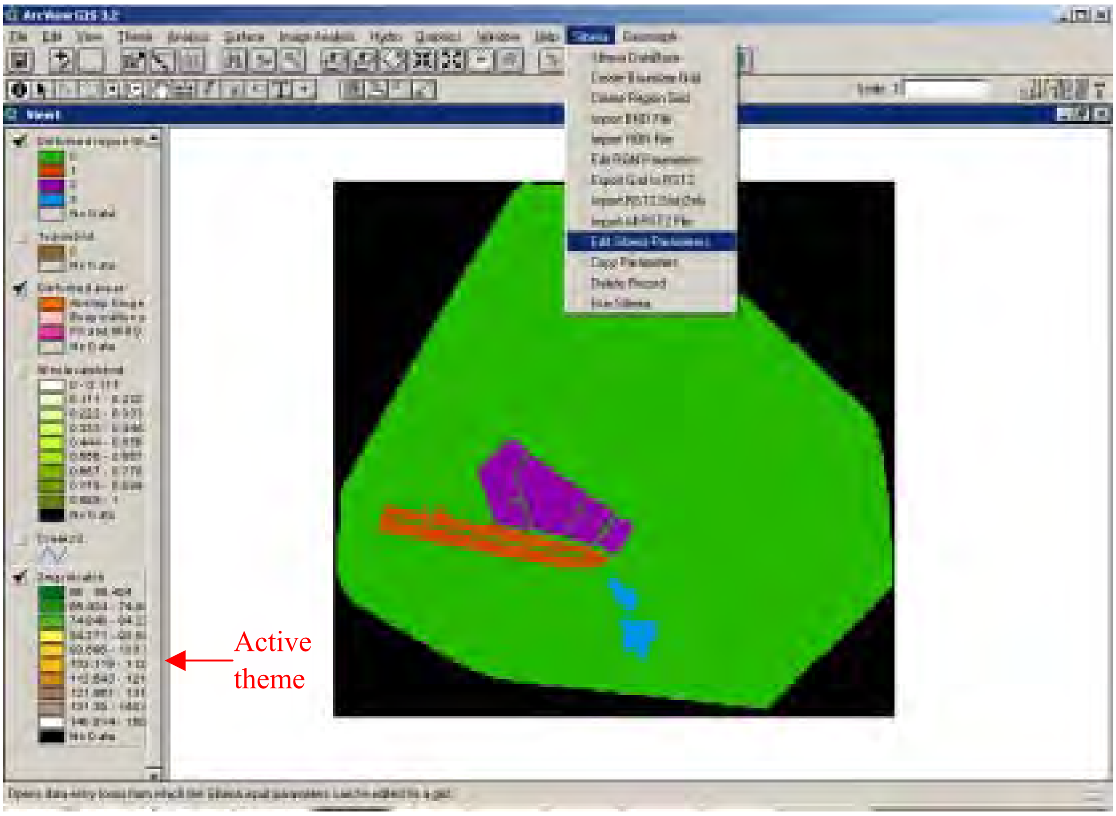


For each of the four regions in the disturbed areas region file, the corresponding parameter values (table 1) were input into the parameter table below. The different regions were selected from the drop down list. For the ‘natural areas’ region file, only the parameter values for the natural region was required.



4.3.2 SIBERIA parameter database

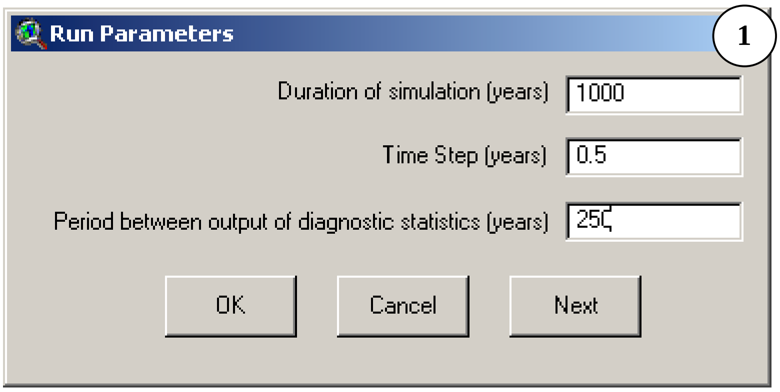
The more general parameter values for the entire catchment area being modelled are required as input into the model. To input these parameter values into the model, the item ‘Edit SIBERIA Parameters’ from the ‘SIBERIA’ menu was selected (ensuring that the original DEM is the active theme) (see below).



Subsequently, SIBERIA input parameters are required within nine parameter tables for the simulation run to commence. The parameter values used in this study are shown in each of the following parameter tables.

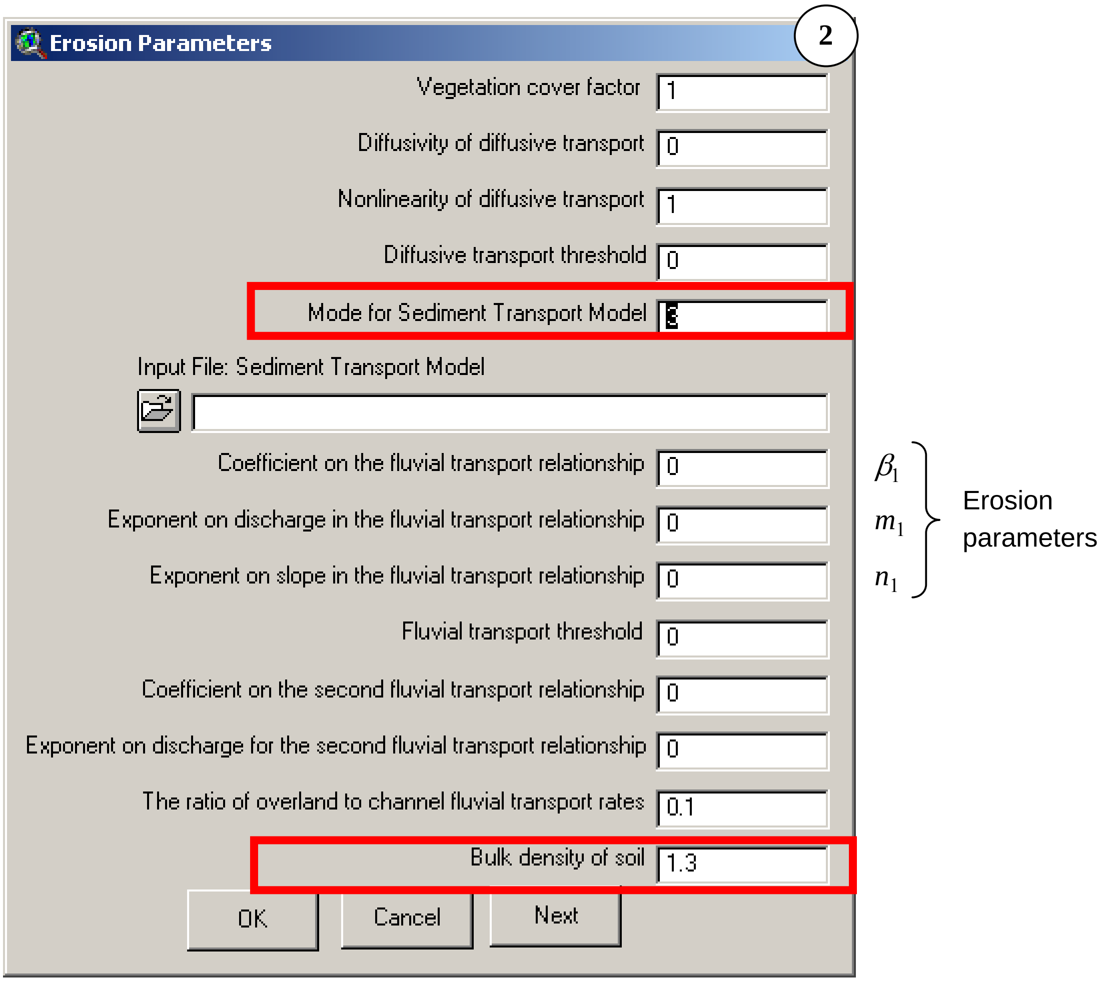
Parameter table 1 – Run parameters

The first set of SIBERIA parameters that need to be input into the model are the ‘run parameters’ which simply describe the simulation run (see below - parameter table 1). It should be noted that the Time Step interval controls the numerical stability of the mass balance algorithm within the SIBERIA model code (Willgoose 1992). Generally, the larger the time step the faster the run, which may compromise the accuracy of the simulated outputs. If the input time step is negative (ie –0.5 y), the SIBERIA code will determine the optimal timestep based on certain criteria which ensure good performance in SIBERIA. The timestep will adaptively change throughout the simulation, adjusting to current conditions. The simulation run parameters used in this study are shown below in parameter table 1.



Parameter table 2 - Erosion parameters

The 'Mode for Sediment Transport' parameter value is critical for the model to run successfully (highlighted in table 2). The value of 3 indicates that the erosion parameters (β_1, m_1, n_1) for each surface condition have already been defined within the region file (Section 4.3.1). Therefore, these erosion parameters are not required in the SIBERIA parameter database (ie they are given a value of 0 in the erosion parameter table). (This input value is 1 if the model is run on a landform where the surface condition is the same for the entire area. In other words, when there is no region file. In this case, the erosion parameter values must be input into the SIBERIA parameter database.)

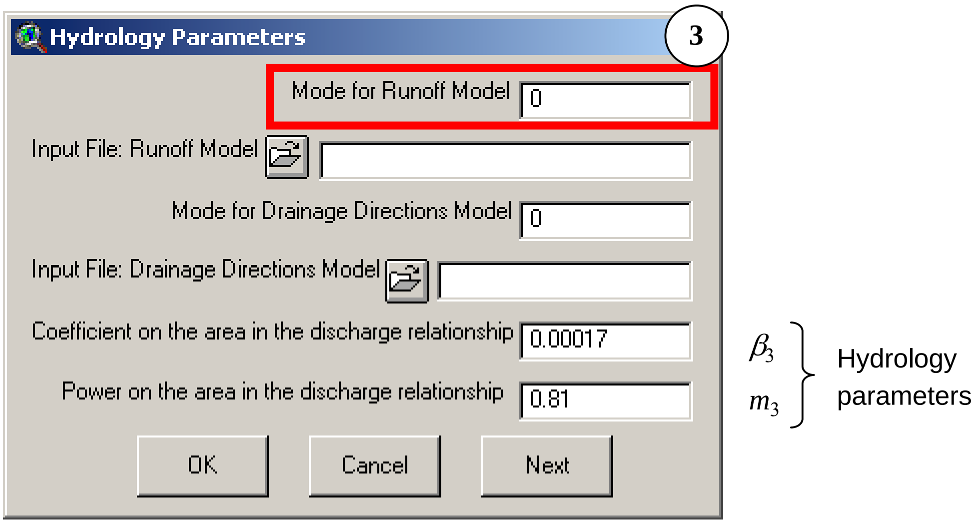


The bulk density of the soil (highlighted in table 2) is considered to be the average value over the whole catchment area. Unfortunately, separate soil bulk density values for the different surface conditions cannot be input into the corresponding region files (Section 4.3.1).

Parameter table 3 - Hydrology parameters

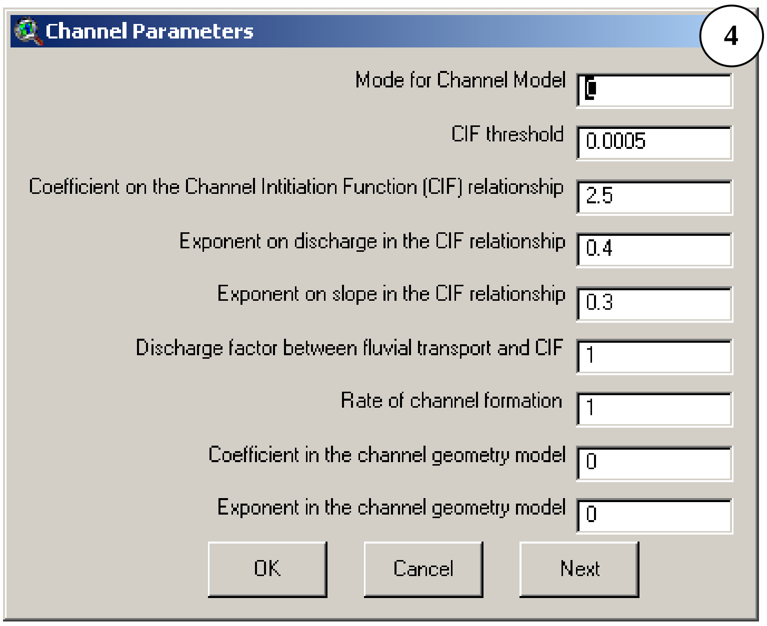
Similar to the erosion parameters, the hydrology parameter values (β_3, m_3) specific to each of the four surface conditions have already been defined within the region file (Section 4.3.1). Therefore, in theory, these hydrology parameters should not be required in the SIBERIA parameter database (ie given a value of 0 in the hydrology parameter table) and the 'Mode for Runoff Model' parameter value (highlighted in table 3) should be 3. However, SIBERIA would not run <u>unless</u> the hydrology parameter values were defined in the SIBERIA database (parameter table 3) and the 'Mode for Runoff Model' parameter value was 0. This means that the model assumes the entire catchment has the same hydrology parameter values, thereby ignoring the hydrology parameter values defined for each different surface condition within the region file. **This was a major flaw within the modelling process. The subsequent simulation results cannot be considered an entirely reliable indication of the erosion and deposition likely to occur on the landform.**

It was therefore assumed that the entire catchment area, including the disturbed areas, had hydrology parameter values which represented the natural surface condition (parameter table 3).



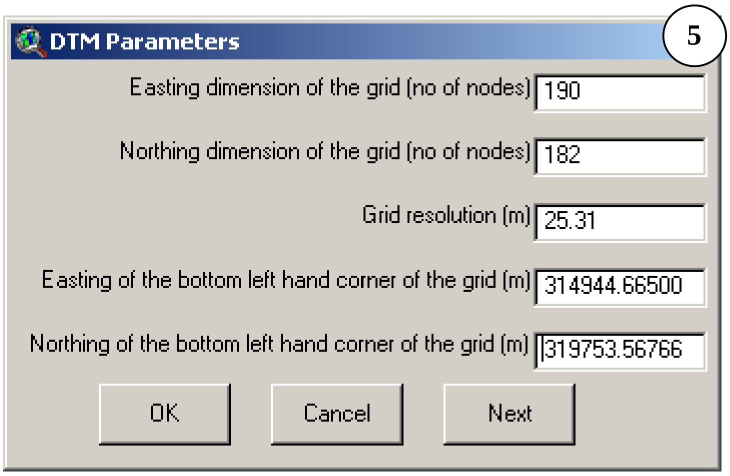
Parameter table 4 – Channel parameters

In this study, the default values were used and the cell values were not edited within parameter table 4.



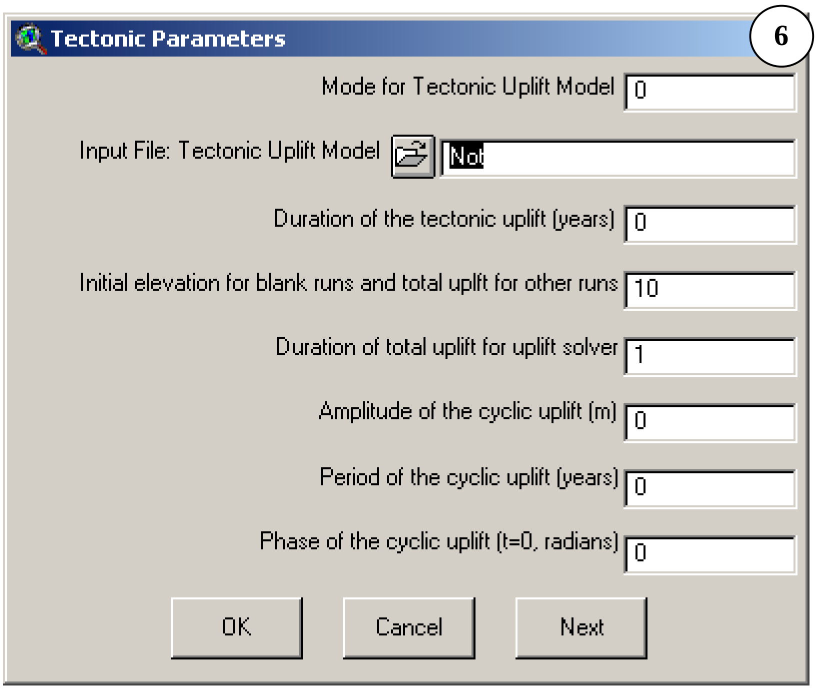
Parameter table 5 – DTM parameters

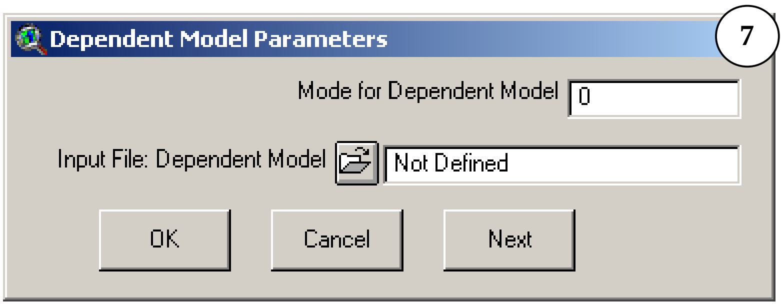
The DTM parameter values are automatically derived within ArcEvolve and should not be changed within this table.

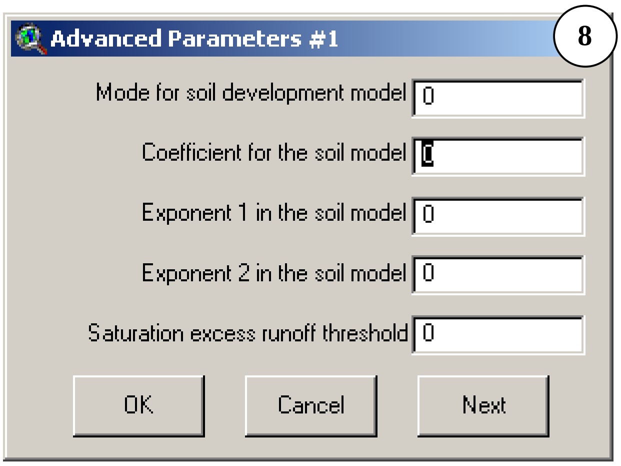


Parameter tables 6-8 - Tectonic Parameters, *Dependent Model Parameters* and *Advanced Parameters #1*

In this study, the default values were used and the cell values were not edited within parameter tables 6 to 8 (shown below).

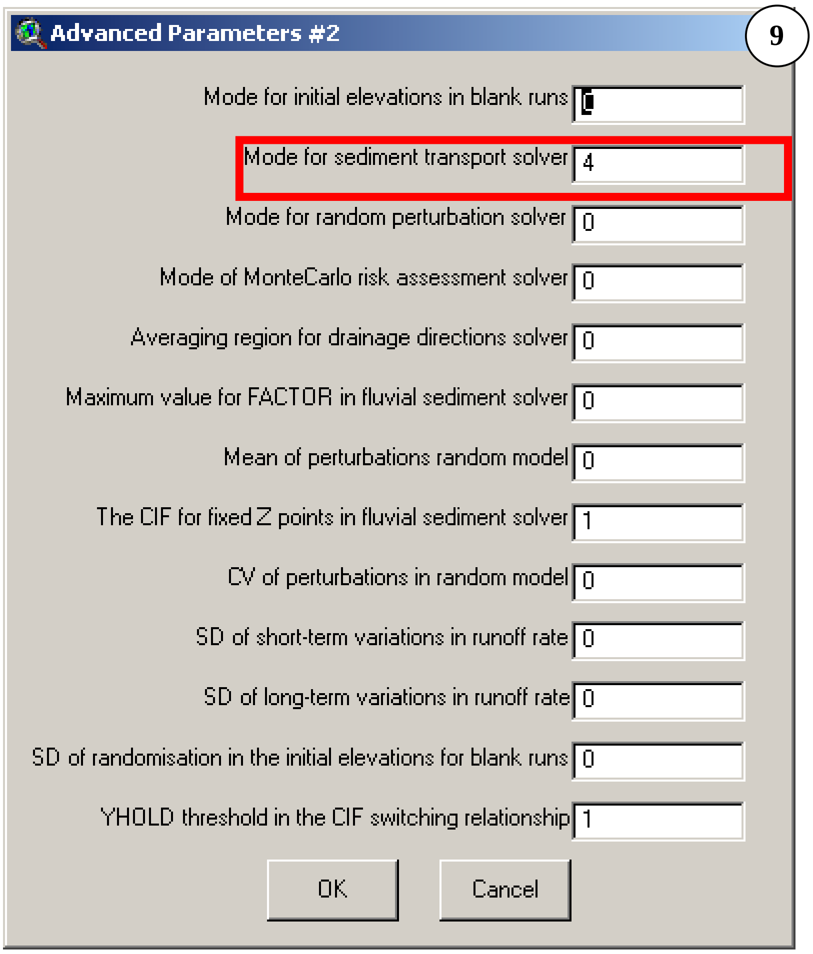






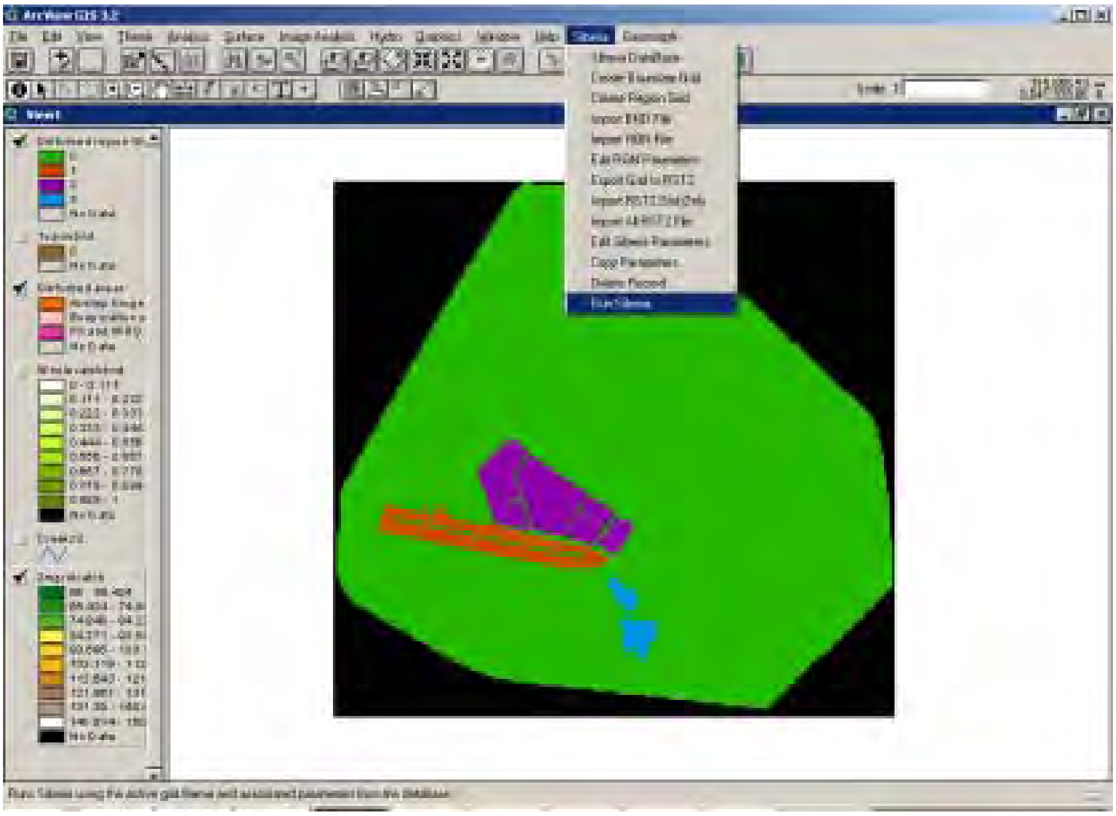
Parameter table 9 - Advanced parameters #2

The 'Mode for sediment transport solver' parameter value is another critical value for the model to run successfully (highlighted in parameter table 9). The value of 4 indicates that the erosion parameters (β_1, m_1, n_1) for each surface condition have already been defined within the region file (Section 4.3.1). (This input value is 1 if the model is run on a landform where the surface condition is the same for the entire area. In other words, when there is no region file.)



4.3.3 Running the SIBERIA model

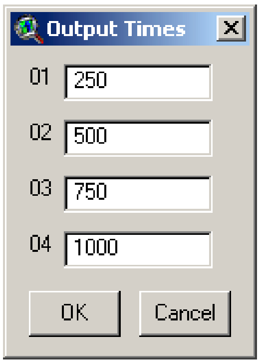
The final step in the process, once the parameter values have been input into the model, is to run SIBERIA. To run the model, the item ‘Run SIBERIA’ within the ‘SIBERIA’ menu was selected (as shown below).



The area to be modelled by SIBERIA, defined by the boundary file (created in Section 4.2.2) and the region file (created in Section 4.2.3), was input into the ‘Siberia Output File Details’ table below. The region file representing the disturbed mine-impacted catchment area was selected as the initial ‘Input Region Grid’, and the SIBERIA program run.

As noted previously, the period of simulation was set in parameter table 1. Depending on the output requirements, the number of the outputs required may be specified. Similarly, the period at which the simulation was to commence may also be specified.

In this study, the simulation period was 1000 y. The frequency with which the outputs are produced may be specified in a separate window (shown below, in this case, output grid files were produced every 250 y). Once the simulation run is complete, ArcEvolve will prompt the user if they wish to import the corresponding grid outputs (250 y, 500 y, 750 y and 1000 y) into the active view.



5 Simulation results

Figure 5 shows the current landform at Nabarlek, which includes the Kadjirrikamamda Creek, Buffalo Creek and West Cooper Creek catchment areas, based on a grid cell size of 25 m. The disturbed areas, such as the evaporation ponds, the mine pit and the waste rock dump, are also shown (fig 5). The landform was modelled for a simulation period of 1000 years.

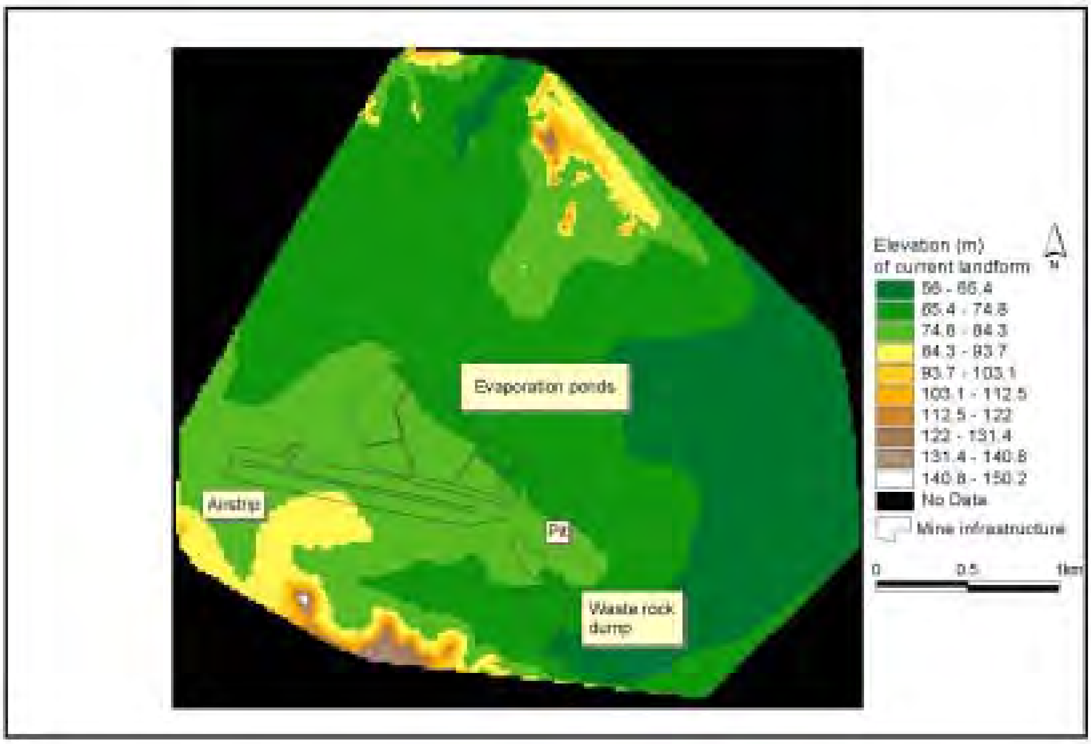


Figure 5 Digital elevation model of the current landform at Nabarlek with disturbed areas superimposed on top

Figure 6 shows the simulated landform of the Nabarlek catchment area at 1000 years using input parameter values derived for the four different surface conditions that exist on the landform (table 1). For impact assessment, the simulated landform for disturbed conditions (fig 6) was compared to that for natural, undisturbed conditions (fig 7). That is, the current landform at Nabarlek (fig 5) was also modelled for 1000 y using SIBERIA input parameter values fitted for just the natural surface condition (table 1). Strictly speaking, this simulated landform is not a true prediction of the surface stability of the catchment area under natural conditions because the DEM used is the same as that used above - which was generated from topographic data collected *after* the mine site was rehabilitated. A pre-mining DEM of the catchment area, which is clearly more appropriate, is unavailable.

Figures 8 and 9 show the simulated erosion and deposition that occurs on the disturbed and the natural landform respectively and indicates that it is likely that the mine will have an impact on long-term erosion and deposition in the catchment area, particularly the areas around the evaporation ponds, the waste rock dump and the airstrip. (The technique used for identifying areas of erosion and deposition on a landform in ArcEvolve is described in Appendix 4.) However, the amount of deposition of sediment that occurs within the channels downstream of these disturbed areas is no different to that on the simulated landform under natural conditions (figs 8 and 9). For example, most of the sediment eroded from the evaporation ponds is deposited on an area immediately downstream of the ponds (fig 8). Therefore, this result indicates that although it is likely that there will be significant incision on the disturbed regions of the catchment area over the long-term, it is unlikely to impact sediment movement in the channels downstream, particularly at the confluence to Cooper Creek.

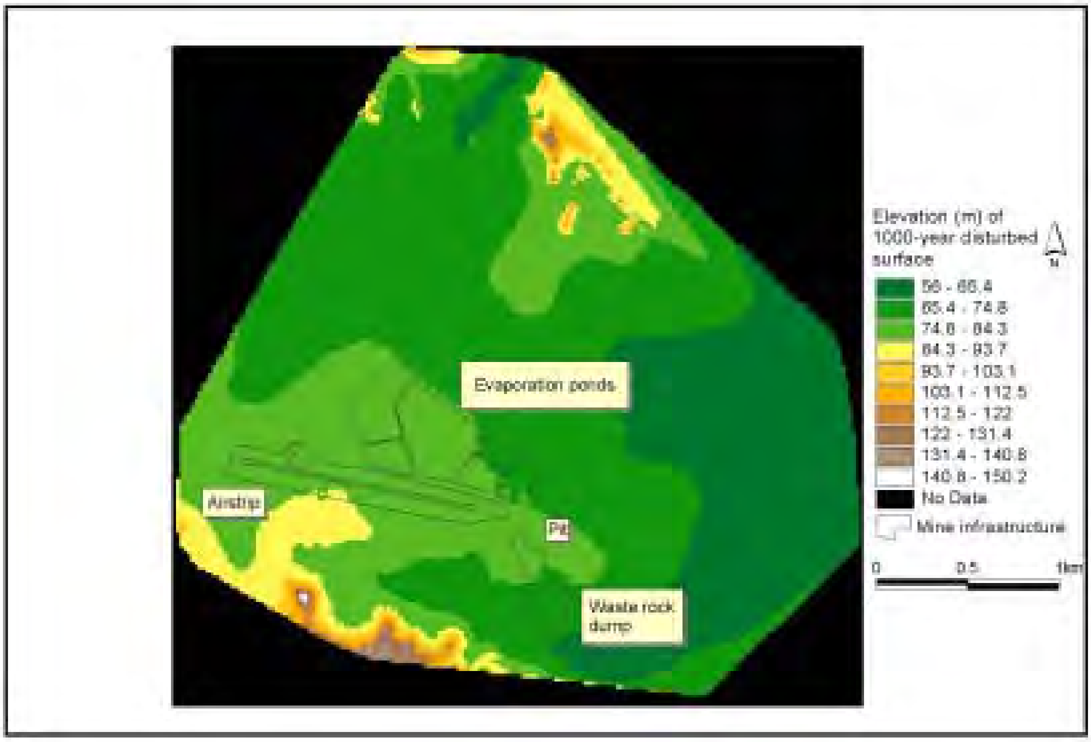


Figure 6 Simulated landform at Nabarlek at 1000 y under disturbed conditions

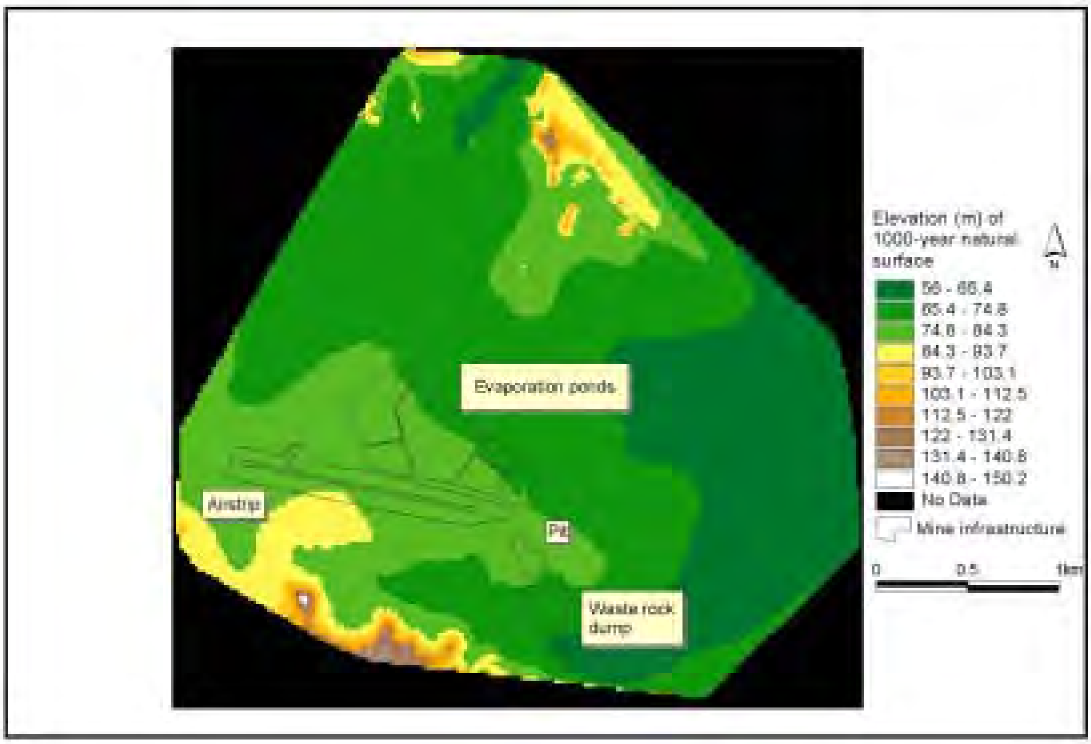


Figure 7 Simulated landform at Nabarlek at 1000 y under natural, undisturbed conditions

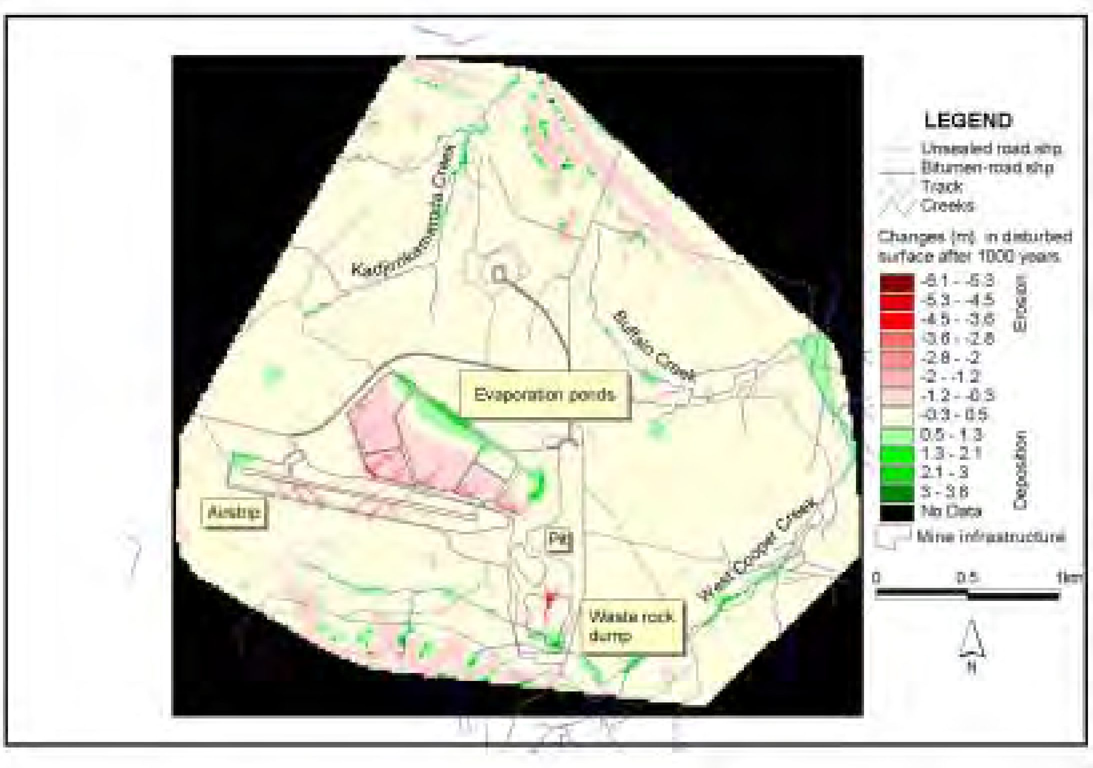


Figure 8 Erosion and deposition on the disturbed landform at 1000 y.

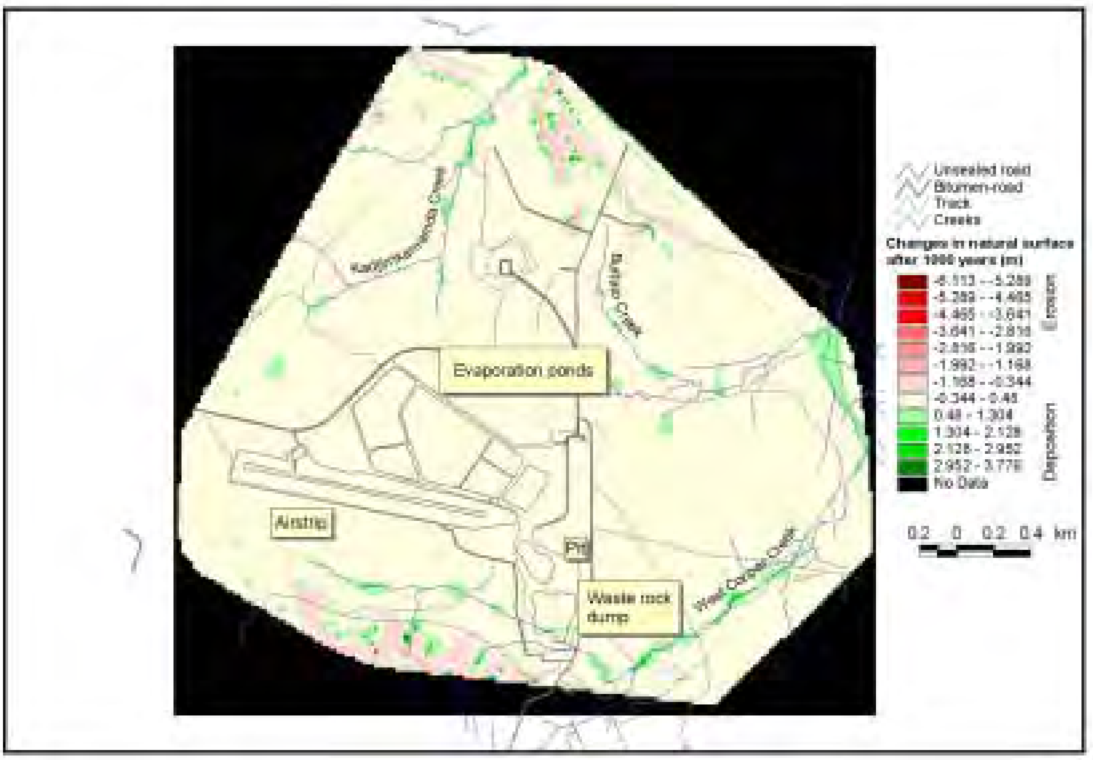


Figure 9 Erosion and deposition on the landform at 1000 y under natural surface conditions.

5.1 Discussion

As discussed above (Section 4.3.2), the simulated landform at 1000 y was derived under the assumption that the entire catchment area, including the disturbed areas, had hydrology parameter values which represented the natural surface condition. The model was unable to assign different hydrology parameter values to the different surface conditions within the catchment area. As a result, the simulation results for the disturbed landform (figs 6 and 8) cannot be considered to be an entirely reliable indication of the erosion and deposition likely to occur on the landform, particularly on the disturbed areas.

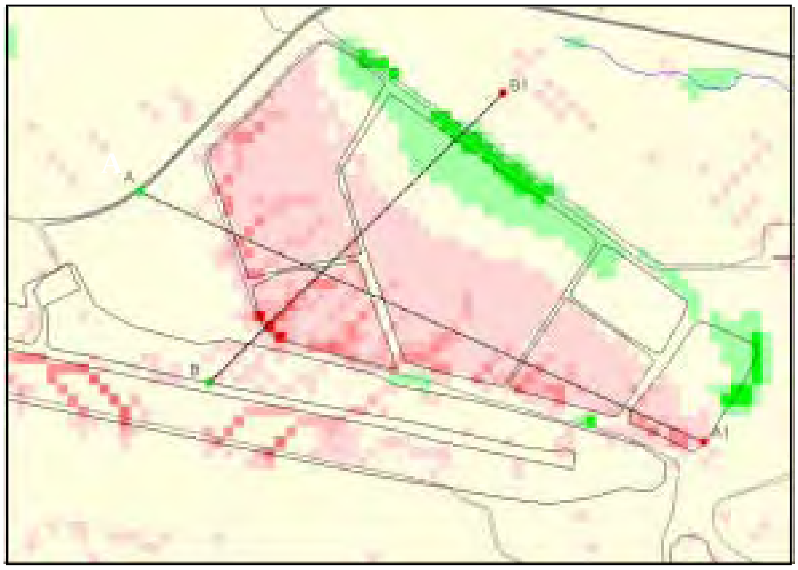
For example, the hydrology parameter values fitted for the surface condition of the evaporation ponds are different to that fitted for the natural surface (table 1). In particular, the β_3 value fitted for the surface condition of the evaporation ponds is two orders of magnitude lower than that fitted for the natural surface. Therefore, it is likely that the simulated erosion on the disturbed landform on the evaporation pond area shown in figure 8 is overestimated (Evans et al 1998). To illustrate this, the entire catchment area was remodelled, in this case, assuming that the entire catchment area had hydrology parameter values which represented the evaporation pond surface condition. This was considered to be the 'best estimate' of sediment movement on the evaporation pond area over the long-term. Cross sections were taken across the evaporation pond area on this simulated landform and compared to that predicted at 1000 y -

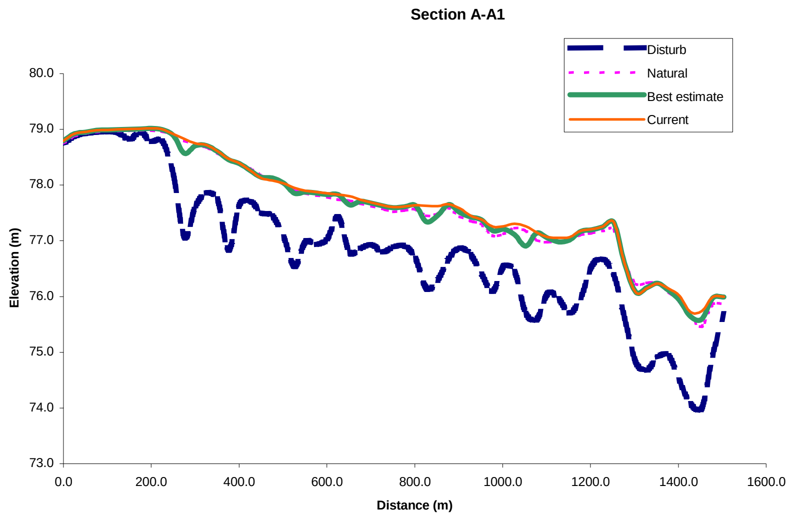
1. Under disturbed conditions using hydrology parameter values fitted for the natural surface (fig 8), and
2. Under natural conditions (fig 9).

One cross section was taken perpendicular to the valleys (section A-A1) and the other along the length of one of the larger valleys (Section B-B1). As expected, the cross-sectional analysis shows that using the natural hydrology parameter values for the entire catchment area will overestimate valley depth (section A-A1) and valley length (section B-B1) on the evaporation ponds in the long-term (fig 10). (These cross sections were derived in ArcEvolve using the Profile Extractor extension, which was downloaded free of charge from the ESRI web site: http://support.esri.com/index.cfm?fa=homepage.homepage)

The hydrology parameter values fitted for the surface condition of the airstrip are also different to that fitted for the natural surface (table 1). In this case, because the β_3 value fitted for the surface condition of the airstrip is higher than that fitted for the natural surface, it is likely that the simulated erosion on the disturbed landform on the airstrip shown in figure 8 is underestimated. The hydrology parameter values fitted for the surface condition of the WRD and mine pit area, however, are very similar to that fitted for the natural surface (table 1). In this case, it is likely that the simulated erosion and deposition on the disturbed landform is reliable.

Clearly, the model's inability to assign different hydrology parameter values to the different surface conditions within the catchment area is a major limitation of the current model. Until this is addressed, the model should not be considered reliable to provide a quantitative estimate of sediment movement in a region over the long-term. It should only be used to provide a preliminary estimate of likely landform stability.





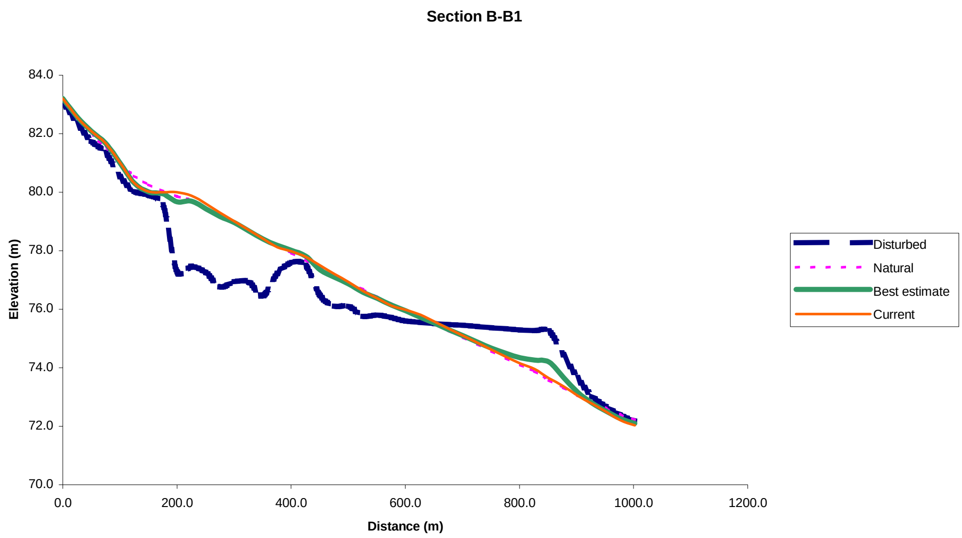


Figure 10 Section A-A1 and B-B1 through the simulated landforms at 1000 y under disturbed and natural conditions

5.1.1 Denudation rates

The denudation rate calculated for the undisturbed surface over a period of 1000 years was 0.009255 mm y^{-1}. The denudation rate for the same period on the disturbed surface was 0.025599 mm y^{-1}, more than an order of magnitude higher than that on the natural landform. (The simple calculation of the denudation rate of a landform is one of the features of ArcEvolve. In this case, the grids which represented the simulated landform and the current landform were selected in ArcView. Using the 'Denudation Rate' option under the *Geomorph* menu, the denudation rate of the simulated landform was produced.)

5.1.2 Additional functionality within ArcEvolve

Although not used in this study, ArcEvolve provides additional functionality to assist with the interpretation and analysis of SIBERIA outputs. Standard gemorphic statistics used to assess landform evolution – such as width function, hypsometric curve, cumulative area diagram and area-slope relationship have been incorporated into the ArcEvolve extension through a *Geomorph* menu. The output of each function in ArcView is a chart and table. However, the data can be exported from ArcView into more specialised 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.

The **hypsometric curve** 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.

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.

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. Various forms of the width function have been identified including the normalised width function (Mesa & Mifflin 1986), standardised width function (Naden 1992) and a simplified form of the width function (Hancock 1997). The original form and simplified form of the width function have been adapted for implementation within ArcEvolve.

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). 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.

The **area-slope** relationship relates the area draining through a point (A) to the slope at the point (S). The area-slope relationship for a catchment has been reported by many authors as having the form;

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

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

6 Conclusions

A preliminary assessment was made on the surface stability of the catchment areas affected by the Nabarlek mine using the landform evolution model SIBERIA. The majority of the sediment movement on the rehabilitated landform over a 1000 y simulation period occurred on the evaporation ponds, the waste rock dump (WRD) and the airstrip. The eroded material from these areas was deposited immediately downstream of their respective areas and, therefore, remained on the mine site. As a result, it is unlikely that there will be an increase in sediment movement downstream of the mine site over the long-term as a result of the mine. In terms of sediment movement and subsequent impacts downstream of the mine, it is considered that the rehabilitated landform is relatively stable over the long-term.

However, the application of the SIBERIA model to the Nabarlek catchment area has highlighted a number of limitations with the current model. The major limitation of the model is that:

- The model assumes the entire catchment has the same hydrology parameter values. In other words, different hydrology characteristics associated with different surface conditions on the landform cannot be incorporated within the model. As a result, the simulation results for the Nabarlek catchment area cannot be considered to be an entirely reliable indication of the erosion and deposition likely to occur on the landform, particularly on the disturbed areas.

Another limitation of the model is that:

- The SIBERIA model cannot process or analyse grids with an array in excess of 250 x 250 cells. As a result, for larger areas or catchments, either (1) the cell size of the grid must be increased which may reduce the accuracy and resolution of the modelling, or (2) subdivide the catchment area and model each subdivision separately which compromises the efficiency of the process.

This study has provided a detailed description of the processes and methods for the application of the SIBERIA model, within a GIS environment, to a catchment area. However, until the above limitations are addressed, particularly the first point, the model should not be considered reliable to provide a quantitative estimate of sediment movement in a region over the long-term. It should only be used to provide a preliminary estimate of likely landform stability.

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Appendix 1: SIBERIA, ArcEvolve and Hydrological modeller extension installation

Installation guide for SIBERIA

1. In order for SIBERIA to run in association with ArcEvolve, the following directory path should be created:

C:\program Files\Landtech\eams1.1\

2. The Siberia815.exe file should be copied into the …\eams1.1\ directory

Installation guide for ArcEvolve:

1. Copy the ArcEvolve.avx file to the extensions folder in the ArcView program directory. Depending on the path of installation, the path for the folder may resemble the following:

C:\esri\av_gis30\arcview\ext32

2. Start ArcView. ArcEvolve should now be able to be selected from the list of extensions available through the File – Extensions menu.

Installation guide for Hydrological modeller:

1. Using windows explorer, navigate to

   C:\esri\av_gis30\arcview\samples\ext

   and select three files - hydrov11.apr, hydrov11.avx and hydrov11.hdr

2. Copy these files to

   C:\esri\av_gis30\arcview\ext32

3. Start ArcView. Hydrological Modeller v1.1 should now be able to be selected from the list of extensions available through the File – Extensions menu.

Appendix 2: Aggregating grids

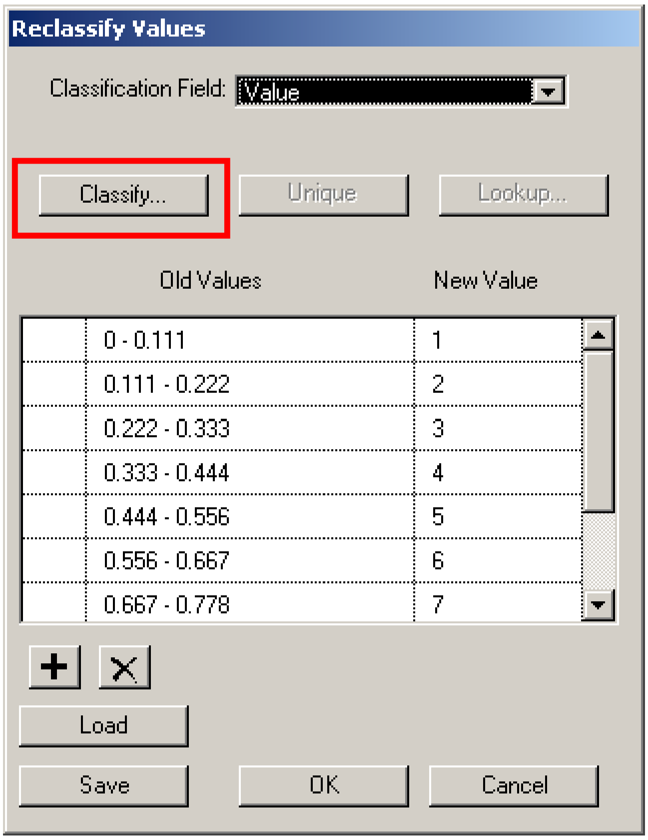
The follow script creates a Grid Theme of reduced resolution by assuming the maximum cell value found in each 3 by 3 block of cells of the original Grid Theme. It assumes that only a single Grid Theme is active. When compiled, the script can be applied to a button in the view containing the grid themes.

```
theView = av.GetActiveDoc
theTheme = theView.GetActiveThemes.Get(0)
theGrid = theTheme.GetGrid
theResult = theGrid.Aggregate(3,#GRID_STATYPE_MAX,FALSE,FALSE)
theGTheme = GTheme.Make(theResult)
' check for error during operation
if (theResult.HasError) then
 return NIL
end
theView.AddTheme(theGTheme)
```

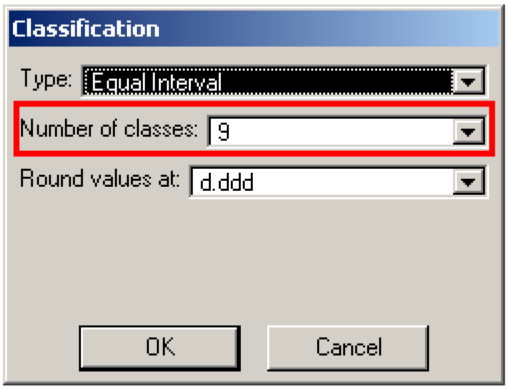
Appendix 3: Reclassifying files

The following steps may be used to reclassify a dataset (be it a boundary file, region file or map calculation):

- Select the dataset in the view and choose the 'Reclassify' command from the *Analysis* menu.
- In the 'Reclassify' dialog box, change the number of classes (eg from 9 to 1) by pressing the 'classify' button.

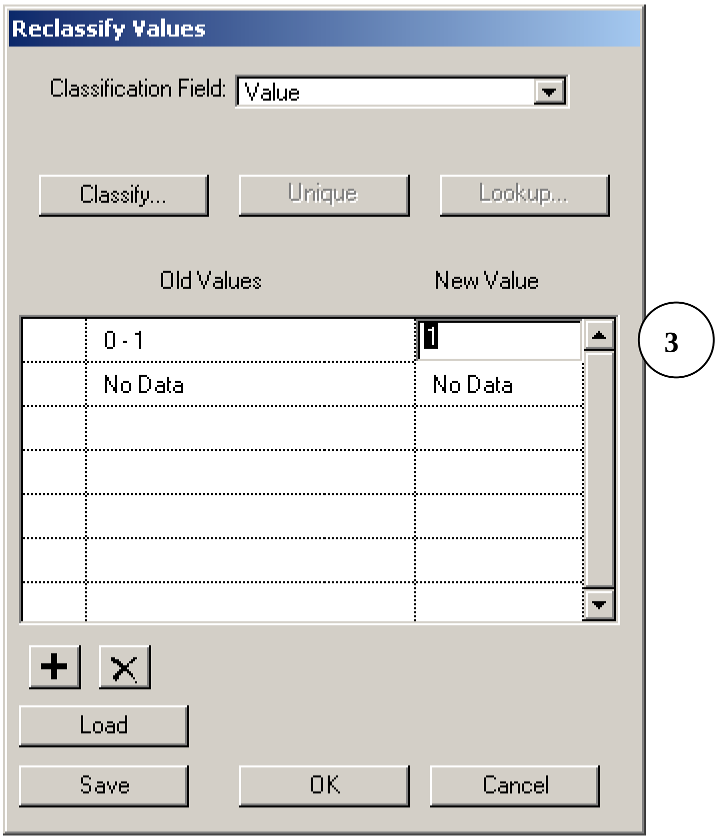


1



2

- Assign a new value of 0 to the one remaining value. Once you have edited the value, you must click on another value (eg the 'no data' cell) **before** pressing OK for the change to take effect.

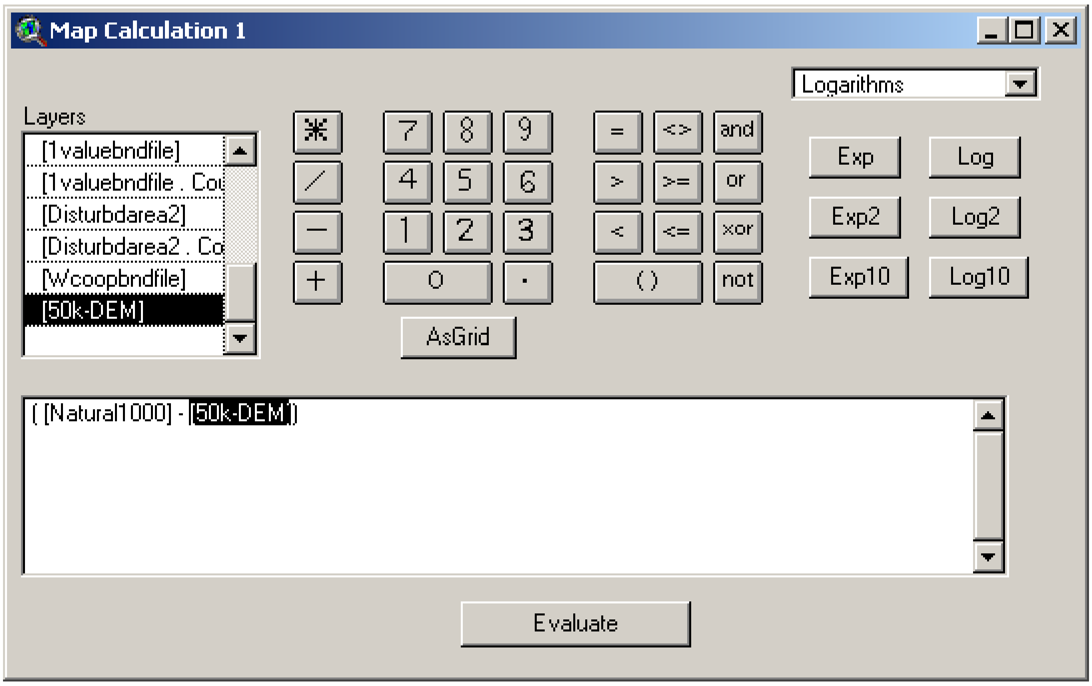


- Re-name the resulting dataset using the *Theme* – 'Convert to Grid' menu item, and store it in the same working directory established for the project.

Appendix 4: Identifying areas of erosion / deposition

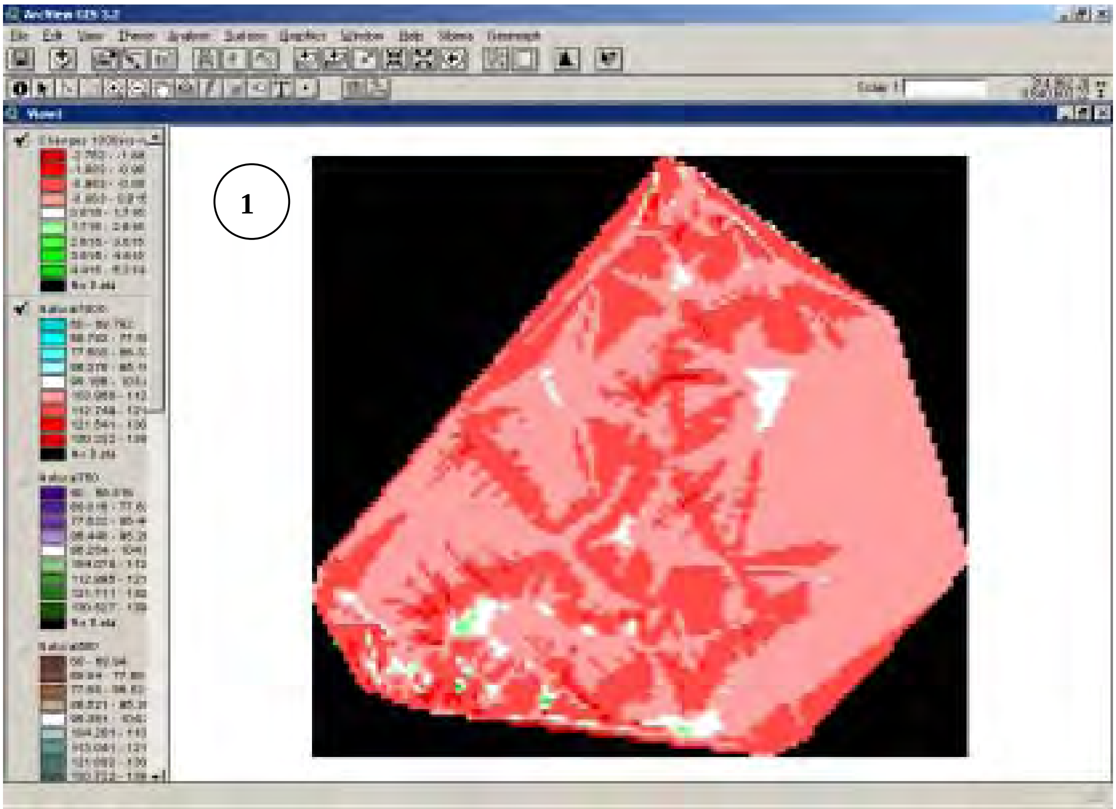
Areas of simulated erosion and deposition may be identified by comparing the current landform to the simulated landform. A process which could be used is as follows:

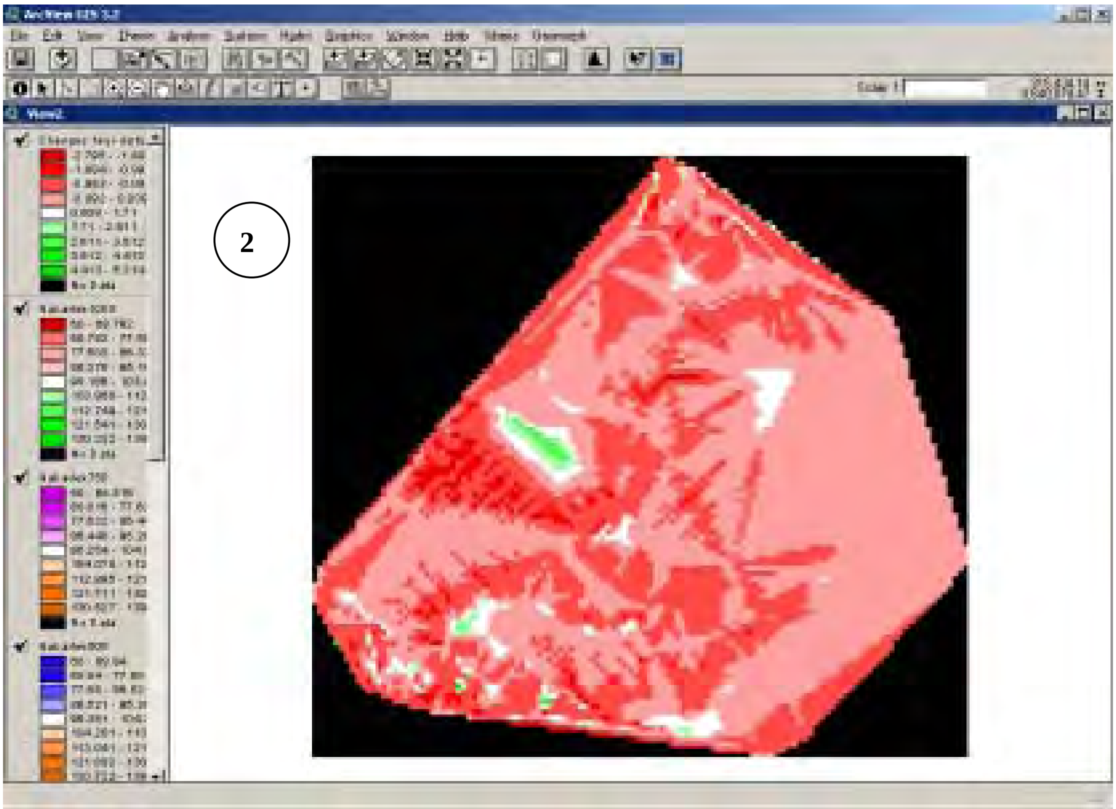
- Select the 'Map Calculator' option under the *Analysis* menu, and build an expression to subtract the grid representing the longest simulation run (eg 1000 y) from the current surface (represented by the base DEM). The resulting map calculation should identify areas of erosion (negative values) and deposition (positive values) on the landform.



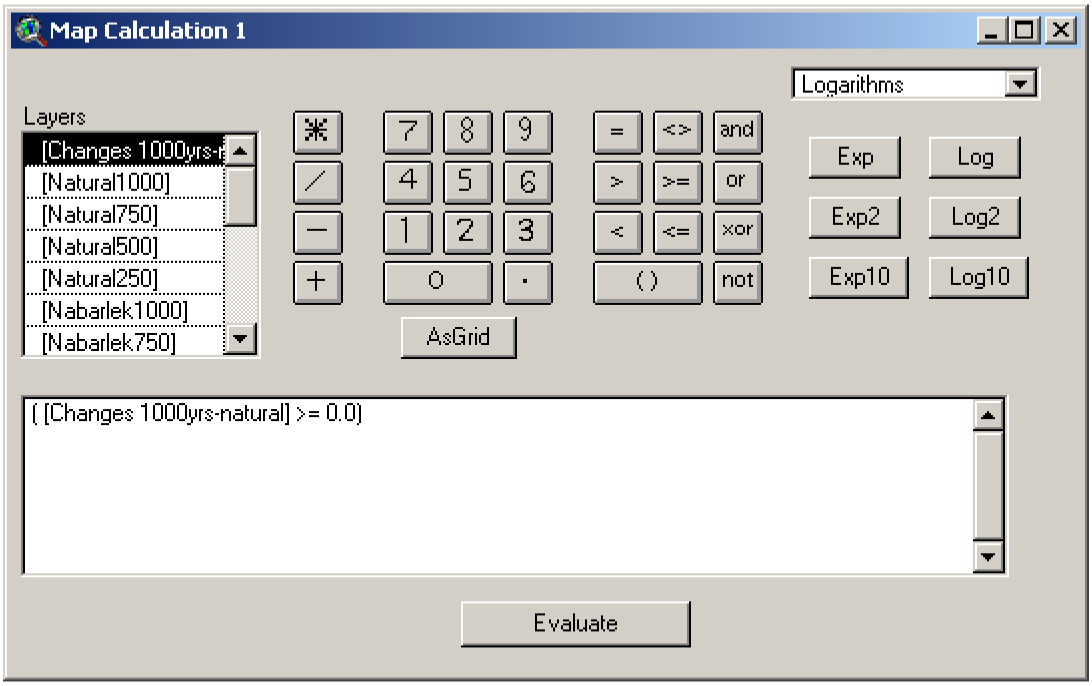
Save the map calculation as a new grid, using the 'convert to grid' command under the Theme menu, to the working directory established for the project.

If the grid indicates no change (eg values are all 0) than the parameters used for running the SIBERIA model will need to be re-edited. In this study, the changes observed over a 1000 y period on the (1) natural and (2) disturbed landform are shown below.





Note that the default output of this equation will be a grid with cell values grouped together in a number of classes. It is likely that one of the classes will contain cells representing both erosion and deposition eg cell values ranging from –0.005 though to 0.78. In order to identify the total area of of erosion and deposition on the surface, select the ‘Map Calculator’ within the *Analysis* menu to refine the results of the earlier equation. In order to produce a new grid surface composed of three classes (all eroded areas; all areas of deposition; and no data), an equation similar to that shown below could be used (where 0.0 is the delineating point between erosion and deposition):



It is important to use the correct file for the equation eg the file representing the cumulative areas of erosion/deposition over the total study period. This will result in a new surface with only three classes - those representing areas of erosion (0), deposition (1) and no data.