Environmental Modelling and Software 114 (2019) 140–151

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Position Paper

Geomorphic design and modelling at catchment scale for best mine rehabilitation – The Drayton mine example (New South Wales, Australia)

G.R. Hancock[a,*], JF Martín Duque[a,b,c], G.R. Willgoose[d]

[a] School of Environmental and Life Sciences, Earth Science Building, The University of Newcastle, Callaghan, New South Wales, 2308, Australia
[b] The Tom Farrell Institute for the Environment, The University of Newcastle, Callaghan, New South Wales, 2308, Australia
[c] Geodynamics Department and Geosciences Institute (IGEO), Complutense University-CSIC, 28040, Madrid, Spain
[d] School of Engineering, The University of Newcastle, Callaghan, New South Wales, 2308, Australia

ARTICLE INFO

Keywords:
SIBERIA landscape evolution model
Natural Regrade with GeoFluv software
Landscape modelling
Geomorphic landform design
Mine rehabilitation

ABSTRACT

Computer modelling and design tools can assist in environmental management. In particular, post-mining landscapes with large volumes of materials require shaping for optimal erosional stability and ecological and visual integration into the surrounding undisturbed landscape. This paper evaluates the complementary capabilities of landscape evolution modelling (SIBERIA) and geomorphic design software (Natural Regrade with GeoFluv). An existing 11.5-ha waste rock dump (Hunter Valley, New South Wales, Australia) served as the study site. The SIBERIA modelling demonstrated that geomorphic design reduced erosion by half that of conventional designs while being able to store an extra 7% of mine waste volume. Additionally, the spatial pattern of gullying was able to be predicted by modelling, which allowed management in subsequent geomorphic design, and successively more stable patterns. In conclusion, the joint use of the Natural Regrade with GeoFluv geomorphic design software with the SIBERIA landscape evolution model showed complementary capabilities for enhancing mine rehabilitation.

1. Introduction

There is a growing recognition that an understanding of geomorphology can greatly improve environmental outcomes particularly for sites that have been subject to large-scale earth movement. This branch of knowledge and practise (including principles, design, software development, modelling, construction and monitoring) is aimed at developing alternative approaches to traditional engineered (graded, linear) landforms in land rehabilitation (such as contour banks or terraces and downdrains). Geomorphic solutions are an area of high interest in mining, as: (1) there is a litany of reported failures of post mining landscapes and associated structures, mostly due to erosion (see: Haigh, 1979, 1980, 1985, 1992; Goodman and Haigh, 1981; Hahn et al., 1985; Sawatsky and Bestead, 1996; Sawatsky et al., 2000; Hancock, 2004; Martín Duque et al., 2015, among many others); and (2) the hydrological, ecological and visual integration and connectivity of traditional stand-alone post-mining engineered landforms with the surrounding terrain is largely neglected, and a growing demand by the public and regulators is requiring that rehabilitation should blend and integrate much better into the surrounding landscape.

The demand for introducing geomorphic principles in mine rehabilitation (or reclamation, as both terms are used with the same purpose) developed in the US and Australia in the late 1970s and early 1980s. Initially, a requirement that is still used today is the Approximate Original Contour (AOC) concept, included in the United States Surface Mining Control and Reclamation Act, SMCRA (1977). This concept made it compulsory that any US mine reclaimed area “closely resembles the general surface configuration of the land prior to mining and blends into and complements the drainage pattern of the surrounding terrain …“. The demand for complementing the drainage pattern of the surrounding terrain introduced a ‘catchment approach’ in mine rehabilitation — using the drainage basin as the fundamental unit for planning mine rehabilitation and guaranteeing hydrological connectivity.

These early writings asked, for instance, for “the integration of the reclaimed surface and drainage network into the surrounding landscape” (Stiller et al., 1980, p. 277) or for designing natural channels “of progressively higher orders and therefore, of greater capacity and cross-sectional area …” (Hannan, 1984, p. 25). Later, a specific handbook on this issue, *Landform Design for Rehabilitation* (Environment Australia, 1998), based on Hannan's book, stated that (referring to the drainage lines): “Gradients should be progressively increased as the watercourse

* Corresponding author.
E-mail address: Greg.Hancock@newcastle.edu.au (G.R. Hancock).

https://doi.org/10.1016/j.envsoft.2018.12.003
Received 13 February 2018; Received in revised form 2 December 2018; Accepted 18 December 2018
Available online 21 December 2018
1364-8152/

is constructed further back into the backfilled area …. It also mirrors stable natural landforms, where watercourses become progressively steeper as one moves upstream" (Environment Australia, 1998, p. 20). Essentially, the goal was to replicate the patterns and complexity that landforms have in natural catchments, a topic extensively studied by geomorphology for around 150 years (mostly hillslope and fluvial geomorphology).

However, the capabilities for designing such complex 3D landforms and drainage networks mimicking natural ones (i.e., increasing channel cross-sections downstream, or concave channel longitudinal profiles), with dividing ridge lands composed by S-shaped convex-concave slopes, have not been possible only until very recently, with the development of geomorphic software. In addition, the counterpart difficulty for building such complex landforms and landscapes is now possible with automatic GPS-guidance machine control (Bugosh and Eckels, 2006).

To the best of our knowledge, there are few software packages that could be termed as truly geomorphic design tools for land rehabilitation, based on geomorphic principles. The Talus Royal method has been successfully applied at rock roadcuts in France (Génie Géologique, 2017) and is starting to be applied in rock highwalls at quarries. This method attempts to compress time by designing and building the rock cliffs or slopes that would tend to form and evolve with time, through falls and slides that occur preferentially on weathered or fractured rocks. Equivalent natural cliffs or rock slopes are used as analogues. The Rosgen (1994, 1996) morphological classification of rivers, based on slope, width to depth ratio, bed material, entrenchment ratio or sinuosity, is in itself a geomorphic restoration method. This approach has been widely employed for perennial stream restoration in the United States, including mined sites. RIVERMorph (2017) is a design software based on the principles established by Rosgen (1994, 1996). Rehabilitation of the Canadian oil sands led to the development of a site-specific geomorphic approach for designing sustainable drainage systems (Sawatsky and Beckstead, 1996).

The updates and learnings since the implementation of the AOC concept were the breeding ground for the reclamation method GeoFluv™ — from Geomorphic and Fluvial (Bugosh, 2000, 2003). GeoFluv is a geomorphic method for land rehabilitation that is able to reproduce the complexity of natural landforms and drainage networks within catchments, which become the basic rehabilitation design units. Specifically, it designs mature and stable stages of catchments —those which would naturally form by erosional processes for the materials, climate and physiographic conditions at the site. This technique began to be applied at large coal mines of New Mexico (United States) in 1999. Its implementation sought to achieve long-term erosional stability, reduced maintenance, and increased biodiversity as compared to traditional mine rehabilitation landforms (e.g. terrace, berm, down-drains). Natural Regrade is the commercial software (Carlson software, 2017), launched in 2005, that helps users to efficiently make GeoFluv designs in a CAD format. GeoFluv through Natural Regrade has been successfully used in the United States (Bugosh et al., 2016) and Spain (Martin Duque and Bugosh, 2014; Zapico et al., 2018), from where it is extending to the European Union as a recognised Best Available Technique (BAT) for the management of wastes of the extractives industries (JRC, 2018). The method has also been employed in Australia (Waygood, 2014; Kelder and Waygood, 2016), and over South America (Bugosh et al., 2016).

If geomorphic rehabilitation methods and software are scarce, truly geomorphic (landscape, landform) modelling tools are also rare. We are not referring here to soil erosion models, which are more frequent, widely and usefully used in mine rehabilitation, such as the Universal Soil Loss Equation (USLE) and its derivative Revised Universal soil Loss Equation (RUSLE) or the Water Erosion Prediction Program (WEPP) (see Flanagan and Livingston, 1995). While very useful, these models do not have a fully geomorphic/catchment scope — they neither evolve the landforms nor directly consider gullying by fluvial erosion, the latter a common erosion process in post-mining rehabilitation (Hancock et al., 2000). Landscape Evolution Models (LEM) represent the current best practise of geomorphic modelling technology. They offer all the functionality of soil erosion models but operate on a digital elevation model (DEM) grid. They calculate both erosion and deposition at each DEM grid cell and adjust elevation accordingly. In this way, the landscape can evolve through time (Tucker and Hancock, 2010). This allows not just erosion rates to be determined but also to map and represent where erosion and deposition occurs. The models can also visually show what the form of erosion is — i.e. sheetwash, rilling or gullying (Hancock et al., 2013).

There are a number of models that can be used to assess soil erosion and landscape evolution (Tucker and Hancock, 2010). Originally developed in the 1970s (Ahnert, 1976), these models all use a DEM or mesh of grid cells to represent a catchment (Willgoose et al., 1991a,b; Coulthard et al., 2012). These numerical models employ both fluvial and diffusive erosion processes together with climate expressed in rainfall amount and intensity. A summary of key attributes is described in Tucker and Hancock (2010) and Willgoose (2018).

These models are particularly useful for assessing post-mine landscape designs, as they can be input into the LEM and allowed to evolve. Models such as SIBERIA (http://www.telluricresearch.com/) (Willgoose, 1989; Hancock and Willgoose, 2017) are ideal for assessing landscapes at annual time steps and can be run up to thousands of years (Hancock et al., 2016). Hancock and Willgoose (2017) report the authors' use of SIBERIA in projects in Australia, Argentina, Canada, Namibia, Papua New Guinea, Tanzania and the United States. They also outlined its application by consultants globally and that it has the strongest scientific base for landform design in mine rehabilitation (Evans and Riley, 1994; Willgoose and Riley, 1998; Hancock et al., 2003). Other LEMs, such as CAESAR-Lisflood (Coulthard et al., 2012), can run at hourly time steps and can assess the effects of storm events on erosional stability. A new generation of soilscape models are also now available which incorporate both spatially variable hydrology as well as soil material properties (Cohen et al., 2009; Welivitiya et al., 2016). As SIBERIA is the most widely used tool at present, we focus on this model; however, others such as CAESAR-Lisflood could also be used.

Here we describe the combined use of SIBERIA and GeoFluv for obtaining optimal mine rehabilitation outcomes (evaluated in terms of erosional stability). Both tools share key common characteristics: (1) a catchment scale approach; (2) the combined use of hillslope and fluvial geomorphic principles and algorithms; (3) and the concept of maturity in landforms and landscapes (again, at a catchment scale). Despite this, the joint use of SIBERIA and GeoFluv is only starting to be adopted as best practice (Landloch, 2010; Waygood, 2014; Kelder and Waygood, 2016).

In this framework we evaluate the complementary capabilities of two separate computer programs: (1) the landscape evolution (and soil erosion) modelling (SIBERIA) and (2) the geomorphic design software (Natural Regrade with GeoFluv), in order to obtain optimum (stable) landforms through an iterative design-modelling process. Specifically, an 11.5-ha waste dump at the Drayton Mine (New South Wales, Australia) served as the study site. This landscape, built in 2013, was the first GeoFluv rehabilitation example in Australia.

Here, four different landscapes were assessed. The first goal of this research was to evaluate the long-term (100-yr) erosional stability (using the SIBERIA model) of the GeoFluv landscape as built at Drayton Mine. From this information we sought to identify the stability factors for improvement, and then develop an Improved GeoFluv design which was assessed using SIBERIA. Finally, the two GeoFluv alternatives (as-built and improved) were compared with equivalent simulations of two landform designs with the same footprint area and approximate drainage density and waste volume: contour banks, the most common rehabilitation landform in the Hunter Valley of Australia; and natural contouring, a landscaping approach that is becoming widely used. This

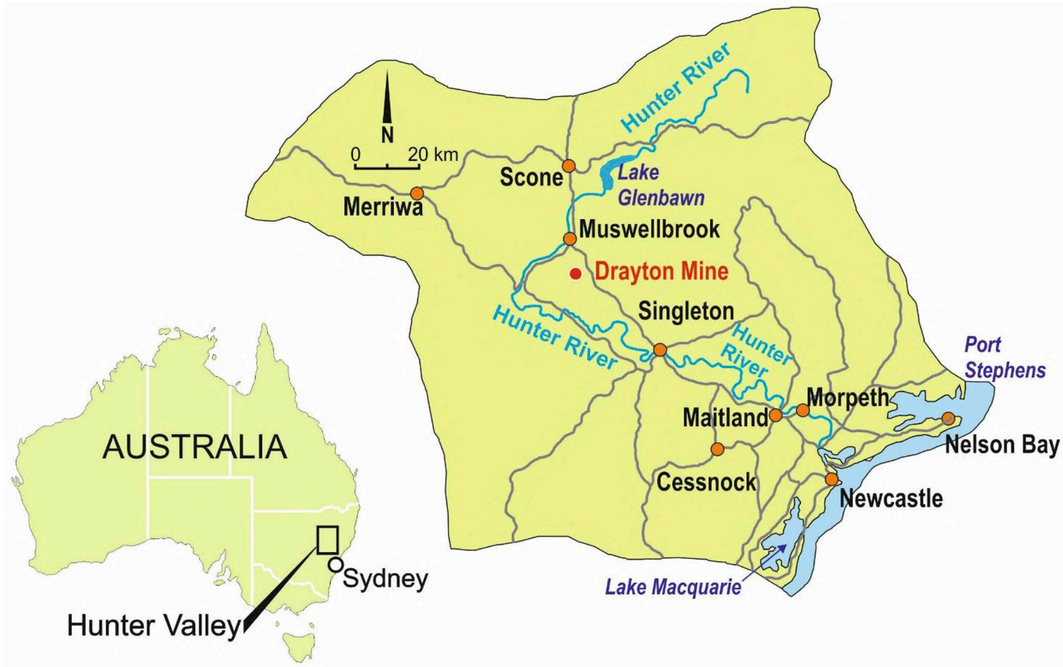

Fig. 1. Location of the Drayton coal mine within the Hunter Valley of New South Wales (Australia).

comparison between four landscapes dealt exclusively with erosion, as the landscape footprint together with soil and vegetation factors remain constant. With this procedure, we seek to contribute for best practise in mine rehabilitation.

1.1. Study site

Drayton is an open cut coal mine located in the Hunter Valley of New South Wales, Australia (Fig. 1), operated by AngloAmerican (during the period of this study). The mine commenced operation in 1982 with production starting in 1983 using draglines together with truck and shovel extraction methods. The mine produced approximately 8 million tonnes of coal per year, mostly for export markets. The mine ceased operation in 2016.

In 2013, an 11.5-ha waste dump (comprised of mine waste rock of sedimentary origin – see Fig. 2a) located on a high point of the mine (Fig. 2b) was re-shaped using GeoFluv-Natural Regrade (Fig. 2c). This site was used as a training and demonstration project for this methodology. The design had four first-order A-type (zig-zag) channels (Rosgen, 1994, 1996) draining the main slope of the waste dump, and three B and C-type meandering channels (Rosgen, 1994, 1996) – one draining the upper platform and two located at the footslopes of the waste dump. The whole design had a stable base level outlet located at a sandstone ledge area (see Fig. 2c). Table 1 shows the inputs used for the design (Bugosh, com. pers.). The construction took place between November and December of 2013 using D9 and D6 bulldozers and an excavator. GPS machine control systems were used to guide the earth movements. A 10-cm cover of topsoil (clay soil) was spread in mid-December 2013. The area was seeded with a mixture of grasses and trees at the end of December 2013.

Several rainfall events occurred during construction causing some incision at the bottom of the built first-order valleys. This was addressed with topsoil spreading. On February 2014 an intense storm occurred and photographs (March 2014) show incision at the thalwegs and rilling at the slopes (Fig. 3). The incised areas were repaired and reseeded between May and June of 2014. Photos of the area taken in September 2014 show an incipient and homogeneous herbaceous vegetation cover (Fig. 3a). The site was revisited again three years after (in September 2017), showing a dense vegetation cover (Fig. 3b), which has largely stabilized the site; although a series of 20-cm (on average) discontinuous gullies exist at the bottom of several of the built valleys (Fig. 3c).

2. Methodology

2.1. Landform design scenarios

The landform design alternatives to be modelled and compared are two GeoFluv designs (as-built, GB, and improved, IG) and two other ones using techniques currently being applied or considered for the coal mine rehabilitation at the Hunter Valley in Australia: contour banks (CB) and natural contouring (NC). For comparison, the main condition was that any design alternative would have the same footprint (11.5 ha), and similar drainage density and mine waste storage capacity (a maximum 10% variation was established as a threshold for this parameter). The design and assessment is an iterative process with the original GeoFluv design modelled using SIBERIA and any flaws then amended also with GeoFluv. The methodology is outlined in Fig. 4.

2.1.1. GeoFluv-Natural Regrade designs

The GeoFluv method is a landform design approach currently used for coal mine rehabilitation in the Hunter Valley (Waygood, 2014; Kelder and Waygood, 2016). GeoFluv™ is the trademark name for a specific, patented, landform design method that uses algorithms based on slope and fluvial geomorphic principles. Natural Regrade is the software that helps users construct GeoFluv geomorphic designs. The complexity of natural stable landforms and drainage networks can be reproduced in a CAD format: S-shape (convex-concave slopes), concave longitudinal channel profiles, sinuosity indexes and patterns, or progressive variation of channel cross-sections with increasing flow downstream, among many others.

The method integrates key aspects of the Rosgen (1994, 1996) morphological drainage channels classification, mostly the Aa+, A, B and C stream types, defining them based on slope, width-to-depth ratio or sinuosity. Here we focus on uplands and low-order drainage basins. GeoFluv-Natural Regrade integrates also mathematical relationships for the geometry of natural meandering channels (Leopold and Wolman, 1960; Williams, 1986).

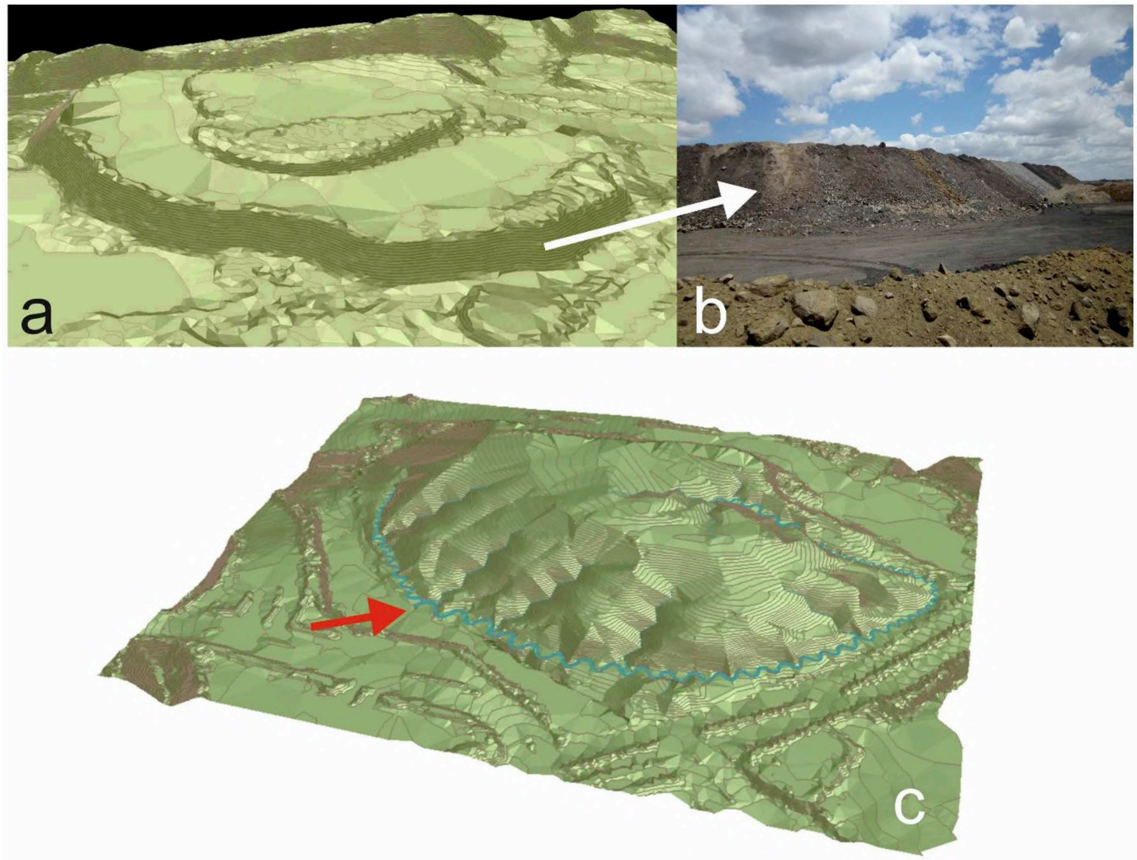

Fig. 2. Rock waste dump at Drayton mine before its GeoFluv geomorphic rehabilitation: (a) 3D view, according to topography of May of 2013; (b) ground photo of 30.10.2013. (c) 3D view of the GeoFluv design for this waste dump (red arrow points out base level). At figure (c), A-type channels of the Rosgen (1994, 1996) classification are those with a zig-zag pattern located at the slopes. BC-type channels of the same classification are those with a meandering pattern, at the toe of the slopes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Inputs used for the GeoFluv geomorphic rehabilitation of Drayton mine (GeoFluv as built, GB). Source: Bugosh (com. pers.).

inputs/settings	source	units	value
Topographic conditions of the design area			
Base level elevation	Site digital	m.a.s.l.	265.38
Base level slope	elevation model	%	- 2
Morphometric inputs from a stable reference area			
'A' channel reach - type of channel with slope > 0.04, according to Rosgen (1994)	Field work at reference area	m	15
Maximum distance from ridgeline to channel's head			40
Target drainage density	GIS analysis of reference area	m/ha	90 (± 20)
Rainfall and hydrological data			
Bankfull rainfall	IFD curves	cm	2.46
Flood prone rainfall			9.18
Runoff coefficient	dimensionless		0.4

GeoFluv-Natural Regrade aims to design mature-stable catchments — the state to which a catchment naturally would evolve by erosional processes to steady-state stability, under the climatic and physiographic conditions at the site. For that, a suitable and stable (mature) reference area has to be identified in the field, to provide initial input values for the rehabilitation design (Bugosh, 2000, 2003). Examples of those inputs are: drainage density, A-channel reach length, maximum distance from ridgeline to channel's heads, width-to-depth ratios and sinuosity for different types of channels, among others. In addition, Natural Regrade uses the 2-yr, 1-hr average recurrence interval (ARI) event to design the bankfull channel dimensions and the 50-yr, 6-hr ARI event to design the flood prone dimensions, since they have been found to be mathematically related with the stream channel pattern (Williams, 1986). The Natural Regrade software has the capacity to use other Intensity-Frequency-Duration (IFD) values according to specific needs or different geographical/climatic characteristics.

For the rehabilitation landform, the input values must be site-specific (measured at an appropriate reference area for each project), using appropriate analogue areas, surface properties and local meteorological records. The input values are therefore not universal ones that can arbitrarily be used at any site. This is a critical point, as some published papers have used words like 'recommended' (Sears et al., 2014) and we emphasize here the importance of obtaining appropriate site-specific project area input values from local reference areas and meteorological records. Once the inputs are established, obtaining a coordinate model of the site is the first step (Fig. 4). The procedure of design is described in detail at the Users' Manual of Carlson Software (http://www.carlsonsw.com/support/manuals/).

The constructed landform (GeoFluv as-built, GB) was designed by Drayton staff. The topography of the resultant landscape was supplied as an ungridded aerial survey using Light Detecting and Ranging (LiDAR) that was undertaken for the site. This data was gridded using ordinary Kriging to a regular 0.2 m by 0.2 m grid. This grid size and gridding method was used for all later landforms.

Geomorphic designs are expected to have long-term stability as they immediately re-establish steady-state or equilibrium landforms with the local environment. Data from monitored GeoFluv-based mine rehabilitations is starting to be available (Bugosh and Epp, 2015; Zapico

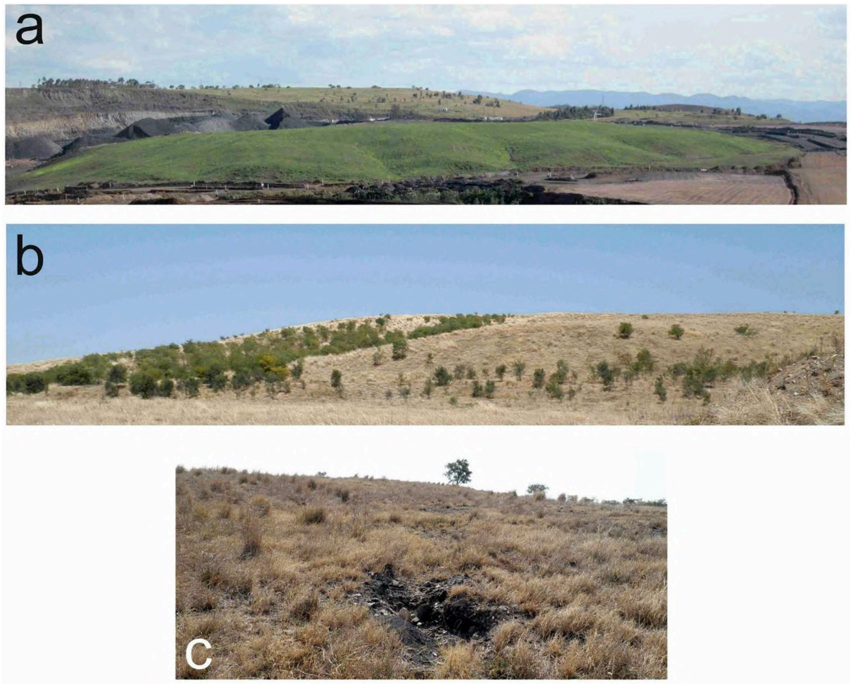

Fig. 3. (a) Panoramic view of the GeoFluv geomorphic rehabilitation at Drayton mine (26.09.2014). (b) Ground panoramic view of the GeoFluv geomorphic rehabilitation (21.09.2017); note one of the valleys where the trees are. (c) Detail of one of the discontinuous gullies that exist at the bottom of several of the built valleys; they have a 20-cm average depth.

et al., 2018). However, in most regions there will be no such previous field-validation. Therefore, computer models (i.e. SIBERIA) are the only method to evaluate the performance of theoretical designs. Fig. 4 shows the feedback process to produce stable GeoFluv designs by their iterative simulation with SIBERIA.

Here, for an objective comparison, we normalized the GB design for volume as there was a difference in volumes between the landscapes. The normalization process maintained the spatial layout of contours but equalised volume. The characteristics of the GB design have been described in the Study Area section.

Finally, as referred, the IG design was created amending instabilities predicted by the SIBERIA modelling.

2.1.2. Contour banks (CB)

Linear hillslopes with contour (or level) banks are the default mine rehabilitation design for many areas including the Hunter Valley. The contour banks consist of linear slopes reaching gradients around 10°, interrupted by channels, or drains, with a bank on the downhill side, constructed accurately on the contour. This erosion control earthwork has been transferred from agricultural practises to mining for retarding runoff and promoting infiltration (Hannan, 1984). These banks interrupt the slopes length at approximately each 10 m of elevation. The contour bank landform was designed with the Carlson software tools of polyline drawing and offsetting, following the design principles by Hannan (1984).

2.1.3. Natural contouring (NC) of surrounding natural terrain

As described in the introduction, there is a global trend in mine rehabilitation of moving from current linear-graded engineered landforms to more natural and complex ones. This is promoting all types of imitations of the shape of natural landscapes with little consideration for geomorphic principles. Common approaches are to try to arbitrarily resemble the pre-mine topography or to imitate the surrounding terrain of the mined lands. Therefore, we considered this pre-mine topography as a viable alternative. The natural contouring that we used was faithful to the definition, since, literally, we fitted the topography of a natural landform from within the mine lease to the waste dump area, matching its configuration, volume and slope gradient, and approximate slope length. The procedure was:

1. Identifying areas surrounding the mine with the same approximate slope and shape of the rehabilitated area subject of study.

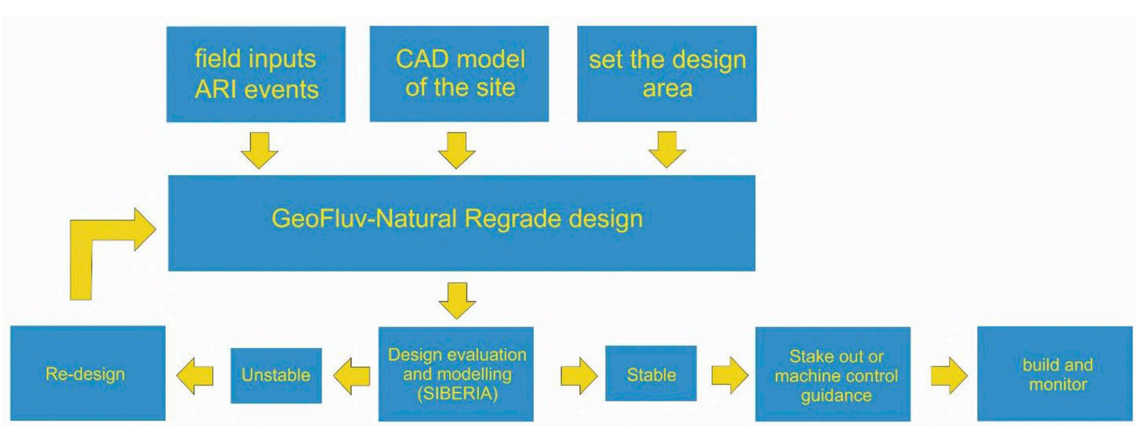

Fig. 4. Diagram showing a GeoFluv design – SIBERIA modelling for maximizing landform stability in mine rehabilitation.

2. Extracting the original (natural) contours by the intersection of a polyline that defines the rehabilitation area.
3. Pasting and fitting the contours at the rehabilitation site with base height corrected.

2.2. Landscape evolution assessment

Here we focus on the SIBERIA model, which has been employed extensively for agricultural and post-mining landforms (Evans and Loch, 1996; Willgoose and Riley, 1998; Hancock et al., 2000, 2008, 2010; Martinez et al., 2009). SIBERIA mathematically simulates the geomorphic evolution of landforms subjected to fluvial and diffusive erosion (Willgoose et al., 1991a,b,c,d; Willgoose, 2018). The model employs well-accepted hydrology and erosion models at annual and longer time scales. The sediment transport equation of SIBERIA is:

$$q_s = q_{sf} + q_{sd} \tag{1}$$

Where q_s (m^3/s/m width) is the sediment transport rate per unit width, q_{sf} is the fluvial sediment transport term and q_{sd} is the diffusive transport term (both m^3/s/m width).

The fluvial sediment transport expression (q_{sf}) is based on the Einstein-Brown equation and models incision of the land surface and can be expressed as:

$$q_{sf} = \beta_1 Q^{m_1} S^{n_1} \tag{2}$$

Where Q is the discharge per unit width (m^3/s/m width), S (metre/metre) the slope in the steepest downslope direction and β_1, m_1 and n_1 are calibrated parameters.

Diffusive erosion, q_{sd}, is:

$$q_{sd} = DS \tag{3}$$

Where D (m^3/s/m width) is diffusivity and S is slope. The diffusive term models smoothing of the land surface and combines the effects of creep and rain splash.

SIBERIA does not directly model runoff but relates discharge to area (A) draining through a point as:

$$Q = \beta_3 A^{m_3} \tag{4}$$

where β_3 is the runoff rate constant and m_3 is the exponent of area (m^3/s/m width).

The advantage of SIBERIA over more traditional erosion models (i.e. RUSLE, Wischmeier and Smith, 1978) lies in its use of digital elevation models for the determination of drainage areas and representation of catchment topography as well as its ability to adjust the landform elevations with time in response to the erosion and deposition that occurs. A more detailed description of the principles underpinning the current version of SIBERIA can be found in Willgoose et al. (1991a,b,c), Willgoose (2005) and Willgoose (2018).

2.2.1. Calibration of SIBERIA

All soil erosion and landscape evolution models require input parameters specific for the site. SIBERIA is no different. The most important parameters relate to the sediment transport equation (Equation (2)). For calibration, the most rigorous method is to use field plots where all rainfall, runoff and total sediment load is collected for a significant number of storm events. These plots should also be maintained for a number of years as it has been found that sediment loads on post-mining landscapes can rapidly reduce through time (Hancock et al., 2016). However, the installation and maintenance of field plots is costly and time consuming and rare at mine sites.

An alternative method is to use high resolution surveying of representative hillslopes with each method having advantages and disadvantages. Laser scanning, digital photogrammetry (both these can be impaired by vegetation), and in recent years airborne LiDAR, are becoming increasingly available. Repeated scans can be used to assess type (i.e. rilling, gullying, sheetwash) and differencing one scan from another allows volumetric assessments to be made and erosion rates calculated. However, at this site (and typical of most mine sites) there are no field plots or survey data available that could be used for calibration. Here we calibrate by using historical data, sediment transport theory and current measurements for the site.

It is well known that the values of m_1 and n_1 (Equation (2)) vary widely but for most fluvial systems they both range between 1 and 3 (Kirkby, 1971). However, n_1 has been measured to be as low as 0.5 in mining applications due to surface armouring (Willgoose and Riley, 1998; Willgoose and Sharmeen, 2006) with, everything else being equal, steeper slopes developing coarser, less erodible, surfaces than flatter slopes (e.g. see the area-slope-diameter plots of Cohen et al., 2009 and Welivitiya et al., 2016). As there were no data available for the site we employed a set of parameters derived for similar materials at another local mine site (Rixs Creek) (Hancock et al., 2008). To calibrate SIBERIA, a fitting process was conducted where β_1 was held constant and m_1 and n_1 adjusted until the form and position of erosion matched the field observation at the site. This process found that values of $m_1 = 2.5$ and $n_1 = 2$ provided the best match to the available field data. These value of $m_1 = 1.5$–2.5 and $n_1 = 1$–2 for Rixs Creek are within the range of values for fluvial process dominated catchments suggested by Kirkby (1971) assuming a spatially uniform sediment production rate. Therefore, the parameters are what could be reasonably expected for the site and materials examined here.

Soil erodibility (β_1) is recognised to be well-described by the RUSLE K factor which can be determined from the material particle size distribution (Evans and Loch, 1996; Sheridan et al., 2000; Hazleton and Murphy, 2007). Here, five individual soil cores (100 mm deep and 65 mm diameter) were collected from representative positions (footslope, midslope and top of slope) on the reconstructed mine landform. A depth of 100 mm was used as this was the average depth of topsoil that was placed over the waste rock. The particle size distribution (PSD) of the five samples was determined by sieve and hydrometer methods with all five samples having similar particle size (average % sand = 51, % silt = 9, % clay = 40; range % sand = 50–54, % silt = 7–11, % clay 39–42). Using the soil particle size classification and K factor (soil erodibility, Wischmeier and Smith, 1978) table of Hazelton and Murphy (2007), the material can be classified as a clay, to which we have assigned a K factor of 0.01. This K factor can be input into the SIBERIA model assuming the surface has an absence of vegetation (Willgoose, 2012).

For many sites where there is bare earth or where the site has been degraded with little or no vegetation (i.e. mine sites with a bare non-vegetated surface or a surface with vegetation removed by fire – discussed later), this erodibility (K) value can be used directly in the model. However, many sites have a rock cover or armour. In the case here, a good grass cover exists after three years post-rehabilitation. Similar to the RUSLE K factor, the RUSLE C (Wischmeier and Smith, 1978) factor can be used to determine the expected erosion reduction due to vegetation. There is quite a lot of data on the role of vegetation and a C factor can be directly determined from tables (Wischmeier and Smith, 1978; Blanco and Lal, 2008) from a variety of sources. Here we use a C value of 0.02, which represents a stand of dense sod like grass (Blanco and Lal, 2008). The SIBERIA β_1 value is then determined by multiplying the K value by the C value (0.0002). Bulk density was calculated from the volume and mass of the cores described above (1.56 t/m^3).

It should be noted that these values are estimated values only. At this site it is not possible to validate the parameters as there is no field plot or survey data available. Therefore, the erosion rate here is indicative only. However, the parameters are very close to the value determined for the nearby Rixs Creek mine site (Hancock et al., 2008), which had an absence of vegetation and similar rilling and gullying to that of the surface examined here. Therefore, the similarity of the parameters at this site to that (determined by independent means) of

Rixs Creek provides confidence in the methods and data.

2.2.2. SIBERIA simulations

The SIBERIA model was run for all four landscapes using the parameters described above. As all post-mining landforms have a bare surface devoid of vegetation, SIBERIA was run for an initial period of three years with an erodibility representing a bare surface ($\beta_1 = 0.01$). This three-year period represents an initial high erosion rate and allows drainage lines to rapidly form.

At three years β_1 was changed to represent a fully vegetated surface ($\beta_1 = 0.0002$) and the simulation continued for 100 years. This 100-year period, while not geomorphic time, is within the human management time period and allows any landscape design strengths and weaknesses to be identified. It also represents the period of most rapid development of a new landform.

To assess erosion rates the DEM of Difference (DoD) approach was used where the reconstructed landscape at year 100 was subtracted from the initial landscape at year 0. This approach also allows maximum depth of erosion (in this case gully depth) as well as depth of deposition to be determined.

3. Results and discussion

3.1. Landform design scenarios, SIBERIA calibration and simulations

Fig. 5 displays the four-landform designs: (a) GeoFluv as-built (GB); (b) Improved GeoFluv (IG); (c) contour banks (CB); (d) natural contouring (NC). Table 2 shows the footprint and volumetric characteristics of all the modelled designs. Fig. 6 shows both the rilling at the interbasin areas (of the GeoFluv as-built landforms) and a sub-section of the 2014 landscape DEM gridded to 0.2 m after one year of erosion using the SIBERIA LEM, demonstrating that the pattern of modelled rilling matched that observed at the site. Finally, Fig. 7 shows the 100-yr SIBERIA modelling for the four landform design scenarios.

3.2. Long-term landform stability (erosion rates)

Erosion values obtained for the four studied alternatives range between 25.6 and 13.9 t/ha/yr. Ranked from higher to lower erosion rates, they are: CB, GB, NC and IG (Table 3). If erosion rates would be the only factor to be judged for their selection as rehabilitation alternatives, perhaps they all could be 'acceptable' as the values are not high compared to other Australian disturbed landscape systems (i.e. tilled agricultural fields, Bui et al., 2011). And certainly, they are much lower than poor standard mine rehabilitation in other regions of the world (i.e., Spain), where Martín-Moreno et al. (2018) found that erosion rates can be an order of magnitude higher. Also for comparison, the Australian Queensland Department of Mines and Energy uses a range of 12–40 t/ha/yr as a target erosion rate for rehabilitated mine sites (Welsh et al., 1994; Williams, 2000). Elliott and Dight (1986; in Kelder and Waygood, 2016) state that natural landforms in the Hunter Valley (baseline) are expected to erode between 0.4 and 11.8 t/ha/yr.

The IG design has the lowest erosion rate (13.9 t/ha/yr) and the highest waste volume storage (2,465,522 m^3). An additional analysis of this IG design showed that 77.7% of the eroded material is deposited within the first-order subcatchments. This means that the real sediment yield value (sediment exiting the catchment) is 3.1 t/ha/yr. For a global comparison, there are only two GeoFluv-based rehabilitation mine sites, worldwide, that have been monitored in terms of sediment yield. At the La Plata coal mine, in the semi-arid environment of New Mexico, United States, Bugosh and Epp (2015) measured 8.3 t/ha/yr of sediment yield for a GeoFluv-Natural Regrade rehabilitation with topdressing and poorly established vegetation and 5.7 t/ha/yr for a GeoFluv-Natural Regrade rehabilitation with topdressing and significant vegetation establishment (compared with 9.5 t/ha/yr for a neighbour undisturbed native site). Zapico et al. (2018) measured 4.0 t/ha/yr of sediment yield at a GeoFluv-Natural Regrade rehabilitation of a kaolin mine (El Machorro) located in a temperate continental Mediterranean environment of Central Spain.

The CB design did not have very high erosion rates, compared to other traditional mine rehabilitation solutions worldwide (see Martín-

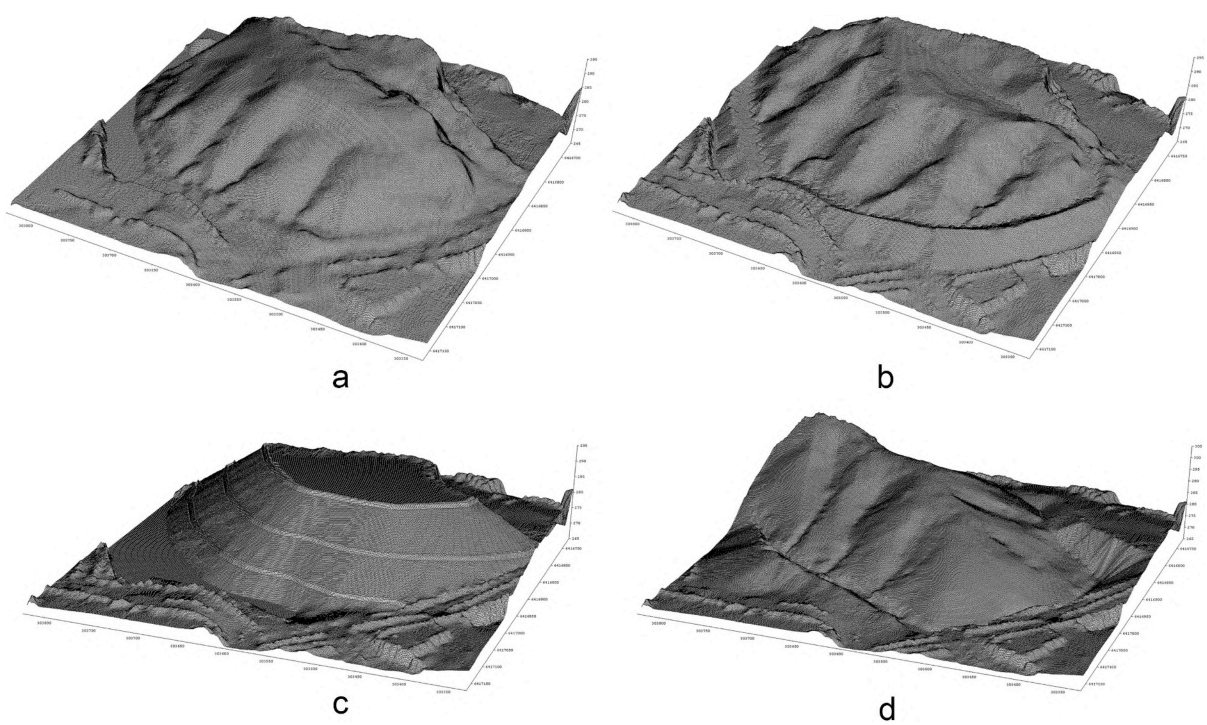

Fig. 5. Landform designs. (a) The landscape as constructed (GB, GeoFluv as built). (b) Improved GeoFluv (IG). (c) Linear slopes and contour banks (CB). (d) Natural Contouring (NC).

Table 2
Footprint and volumetric characteristics of all the modelled designs.

Drayton waste dump (existing or alternatives)	footprint (ha)	heap volume m^3	Variation - m^3 (+) increase (−) reduction	storage cap. Var. %	variation respect to CB %
Original waste rock dump	11.5	2,499,950			
GeoFluv as -built (GB)	11.5	2,582,897	(+) 82,947	(+) 3.3	(+) 12.3
GeoFluv as -built (GB) - normalized	11.5	2,274,899	225,051	(−) 9.0	(−) 1.1
Improved GeoFluv (IG)	11.5	2,465,522	34,428	(−) 1.5	(+) 7.2
contour banks (CB)	11.5	2,300,458	199,492	(−) 8.0	–
natural contouring (NC)	11.5	2,417,494	82,456	(−) 3.3	(+) 5.1

Moreno, 2013, for a compilation of references on this issue). The obtained values (25.6 t/ha/yr) are within what could be considered 'acceptable' in some parts of Australia (12–40 t/ha/yr) for mine-rehabilitated sites, as commented before. This is also in agreement with what Gyasi-Agyei and Willgoose (1996) found, demonstrating that contour banks were more stable than linear slopes without them.

3.3. Erosion process identification and geomorphology

In general, rehabilitated areas with contour banks in active coal mines of the Hunter Valley show a broad acceptable erosive performance. However, there are three key aspects to consider here:

(i) Failures (gullying) occur randomly due to inevitable overtopping of the channel behind the banks, when the storage capacity is exceeded. This can be due to a rain event with a higher intensity than that used for the design, or most commonly, by progressive infilling of those channels.
(ii) When contour banks fail, they tend to trigger fewer but bigger gullies than without contour banks, due to runoff concentration in such drainage lines.
(iii) Although it is not a direct issue related with this research, contour banks do not fulfil the best possible hydrologic, ecologic and visual integration with the undisturbed surrounding landscapes.

As far as the 100-yr modelling of the GB landforms is concerned, they showed two long-term erosion issues:

(i) Runoff was not properly split in subcatchments at the upland areas of the former design, which produce excess runoff towards the slope catchments, increasing the potential of gullying (due to runon). This is a common issue for rehabilitated landscapes, with SIBERIA

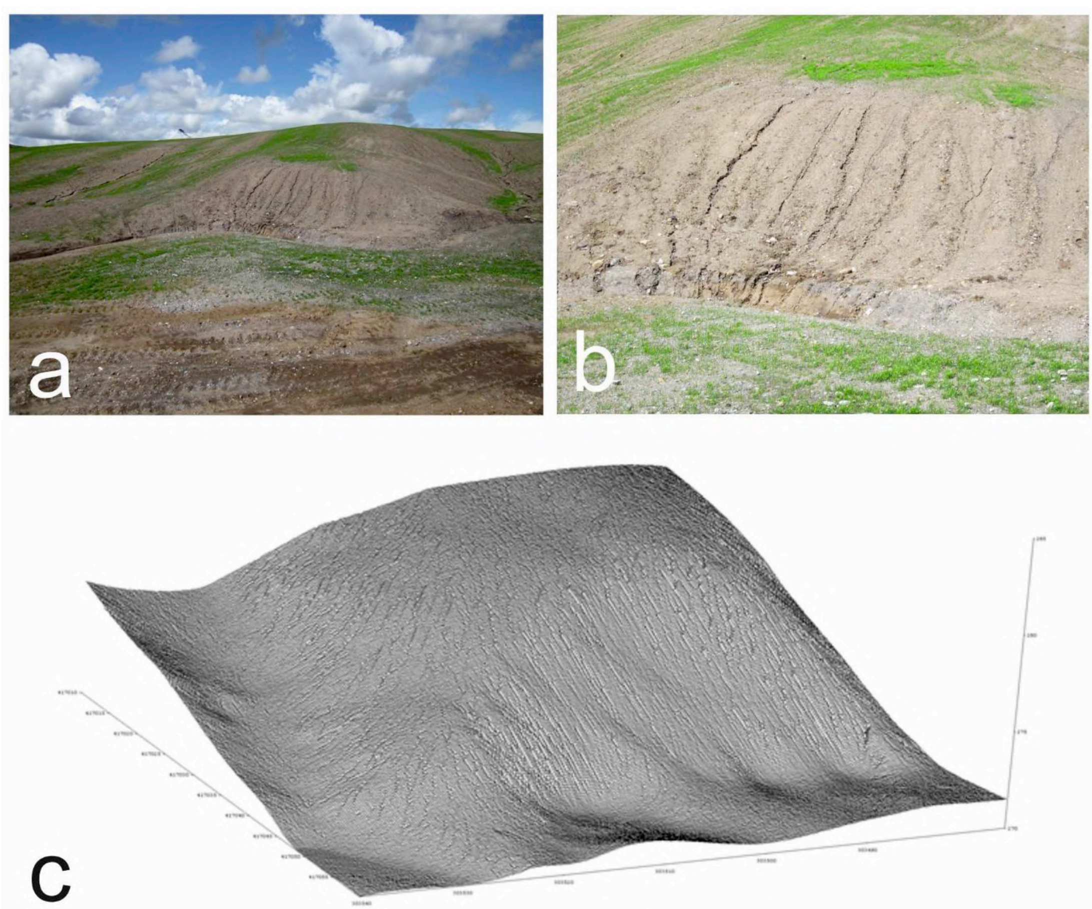

Fig. 6. (a) and (b) rilling at the interbasin areas (of the GeoFluv-as-built landforms. (c) Sub-section of 2014 landscape DEM gridded to 0.2 m after one year of erosion using the SIBERIA LEM. The pattern of rilling matches that observed at the site; see (a) and (b).

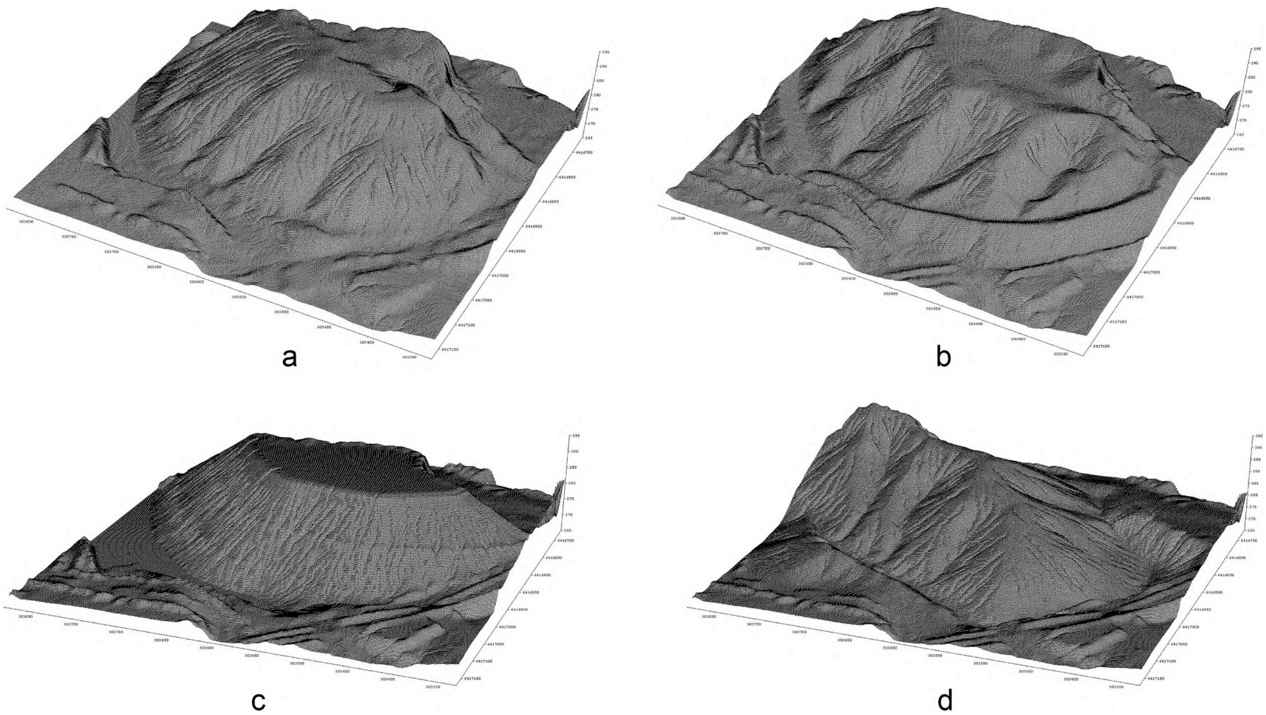

Fig. 7. 100-yr SIBERIA modelling. (a) The landscape as constructed (GB, GeoFluv as-built). (b) Improved GeoFluv (IG). (c) Linear slopes and contour banks (CB). (d) natural contouring (NC).

Table 3
Erosion rates and depths as well as landform characteristics. Negative values represent erosion and positive values deposition. (*) As banks.

Landscape design	Erosion rate t/ha/yr (1.56 t/m^3)	Max erosion depth (m)	Min erosion depth (m)	Waste volume (m^3)	Drainage Density (m/ha)
GeoFluv as-built – normalized (GB)	23.4	−1.43	0.80	2,274,899	158
Improved GeoFluv (IG)	13.9	−1.16	0.35	2,465,522	162
contour banks (CB)	25.6	−2.10	1.40	2,300,458	157(*)
natural contouring (NC)	21.7	−1.57	0.62	2,417,494	127

modelling, mapping and quantifying the process.

(ii) Long-term failure of the constructed earth bank at the base of the structure that encloses the perimeter meander channels.

The forecast of these gullying processes allows them to be considered in future designs. This was performed through an iterative process of GeoFluv-Natural Regrade design and SIBERIA modelling (Fig. 4). It could be argued that the same iterative process could be used for contour banks, but for this landform there is not, literally, much room for topographical improvement (outside the spacing and dimension of the banks), whereas the GeoFluv landforms can be largely changed in topography until a stable design is reached.

Since overtopping is inevitable in the long term, contour banks are a feasible solution while maintenance is guaranteed. This may be acceptable, for instance, if there are economic use of the post-mining land, but they are an option that requires on-going maintenance and associated costs.

For this study site, the NC design had a moderate erosion rate (21.7 t/ha/yr) and developed gullies. This does not occur on the pre-mine landscape that has developed over geological time (Fig. 5d) and has structure (soil horizons) of the soil and substrata. This suggests the unsuitability of arbitrarily trying to imitate the pre-mine topography or that of the surrounding terrain of a mine as a rehabilitation landform alternative. This approach can be well intentioned but lacks geomorphic basis. Unfortunately, the authors have seen an increasing use of NC approaches. A geomorphic approach to mine rehabilitation should not be a matter of simply looking like a natural landform – it must be functionally stable. Often, looking natural at the beginning may lead to widespread erosion as found here. Therefore, this approach is not the best option, given the site and material constraints.

3.4. Spatial patterns in drainage and gullying

Iterative modelling of GeoFluv designs with SIBERIA allowed identification of critical issues leading to instability and gullying. The most critical one was recognising when the 0-order subcatchments and swales were not correctly designed. In these situations, SIBERIA was able to predict gullying for runoff trajectories (Fig. 8). This observation lead to another important observation — that some gullying may occur in the 0-order subcatchments (swales) of the GeoFluv designs and that this would not be a problem if the average erosion values are not high. The key issue here is that GeoFluv designs with runoff split into small subcatchments add spatial predictability to erosion lines, whereas critical erosion problems arise when gullying development is not controlled or predicted: “Drainage network development is a chaotic process but if an initial drainage pattern is imposed, some predictability should be imposed on the eroding system” (Willgoose and Riley, 1998, p. 257). And this is what the GeoFluv designs produce: predicting the gullying-prone drainage lines. Therefore, the use of a LEM is key: with SIBERIA highlighting areas of high erosion (particularly gullies), the geomorphic design can subsequently reduce it.

We interpret the fact that the GB — even with some deviations in

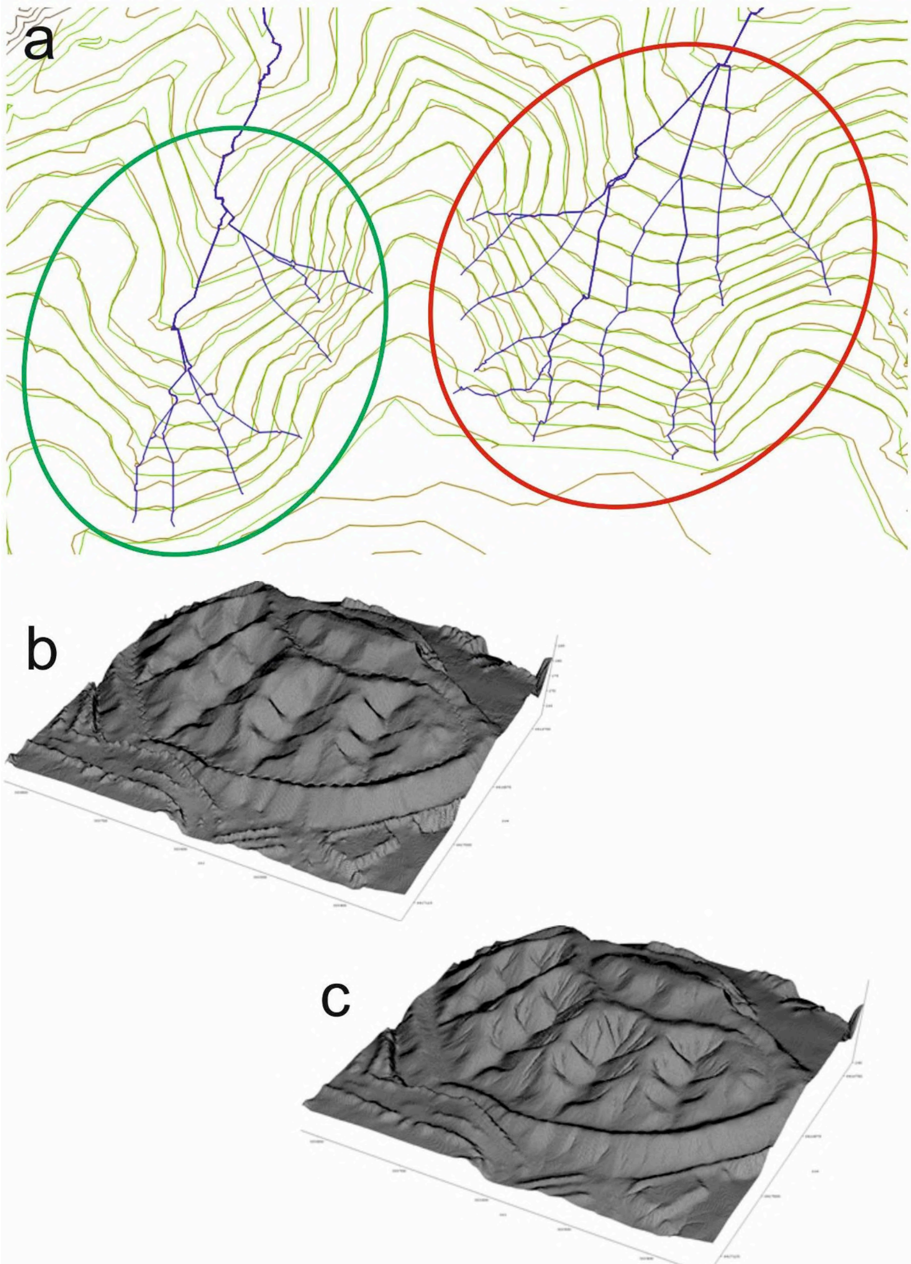

Fig. 8. (a) two first order subcatchments of one improved GeoFluv design in which: the left green ellipse encloses a correct runoff tracking, imposing spatial predictability for the erosion lines, with a decrease in erosion rates; the right red ellipse encloses a wrong runoff tracking, with unpredictability of erosion lines and increasing of erosion rates. (b) This image represents a design in which the runoff tracking has been corrected, so that after its 100-yr modelling with SIBERIA (figure c), the number of erosion lines is minimized, and its location is predicted. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the design and in the building process — and NC — even when not recommended — experience less erosion than CB because both GB and NC include valleys in the landform. Those valleys add drainage predictability and represent more mature landforms than CB, so that they experience less modification by earth surface processes. This reflection has been well explained by Toy and Chuse (2005), p.30: “as the adjustments necessary to establish a steady-state decrease, the prospect for reclamation success increases and the demand for post-reclamation site maintenance decreases”.

That we argue here about the favourable conditions (in terms of erosion) of the natural contouring alternative and the fact that we do not recommend it may seem to be a contradiction, but it is not. This natural contouring solution did not produce high instability at this study site, but a similar approach in another context could be very unstable, introducing high unpredictability. Science-based design and modelling tools (e.g. the QUEL model, Ibbitt et al., 1999; Willgoose, 2001) should always be involved in landform design processes.

Following the same reasoning, one of the problems with the contour banks alternative is that the spatial prediction of gullying formation and evolution is low. A visual interpretation of the pattern of gully formation for the contour bank solution (see Fig. 7c) shows a dendritic organization of the gully network, with multiple captures between rilled and gullied microcatchments, leading to a chaotic and unpredictable drainage network development process. This is also reflected in higher depths of the gullies for contour banks (Table 3). This gullying unpredictability can become more critical under extreme rainfall. The gullying resulting from contour banks failures is a symptom of the adjustments of the geomorphic system trying to redevelop a new drainage network, which has been completely obliterated by a linear slope, whereas the other alternatives have an initial drainage network. And within those three alternatives with a drainage network, the main improvement in the IG landform (compared with GeoFluv GB, which performs similarly to other landforms in terms of erosion rate) has been the proper splitting of the runoff in concave 0-order subcatchments, avoiding long-term failures and unpredicted gullied catchments captures.

3.5. Additional considerations

The GeoFluv geomorphic rehabilitation at this mine (11.5 ha) was a demonstration site. We maintained the exact footprint (11.5 ha) and similar characteristics (waste volume and drainage density) for all the designs (compared to the GB solution). But it has to be stressed that, for a solution to be integrated at a mine scale (for a typical Hunter Valley coal mine), there is no need to have such a high drainage density as the one that was built (158 m/ha). The reason is that the drainage density of the reference area is lower: 90 (± 20) m/ha (see Table 1). High drainage densities imply short slopes (a 60 m slope length is typical of GeoFluv designs for 158 m/ha), which add difficulty and extra expense in construction. There are also difficulties in fitting the channel convexity (40 m of distance of Ridge to Head of Channel in this case, as identified in the reference areas), meaning that most of the slopes would be convex. Slope lengths longer than 100 m, which fit well within a drainage density of 90 m/ha, would be more reasonable and feasible. It is not easy to predict how a more realistic drainage density for all four designs (according to reference area, 90 m/ha) would affect the outcome and the interpretation of the results which are presented here. Theoretically, GeoFluv designs would be even more stable, since a lower drainage density would mean more concave reaches at the base of the slopes, whereas a lower drainage density in contour banks (less length of banks per hectare) would imply, theoretically, more instability. But this reasoning is only applicable *circa* 90 m/ha, because lower values in GeoFluv designs would mean gullying, until reaching that 90 m/ha of equilibrium state.

The results also demonstrate that the GeoFluv designs and the most common landform rehabilitation solution of the Hunter Valley, contour banks, can store approximately the same volume of waste (see Table 2). Specifically, the GB stores 12.3% more of waste volume that contour banks, and the improved IG solution is able to store 7.2% more, but in this latter case having about half of erosion rate.

4. Conclusions

Here we demonstrate and assess the first systematic integration of the use of geomorphic design (GeoFluv-Natural Regrade) and assessment using a landscape evolution model (SIBERIA). Unstable design issues were identified using SIBERIA and removed using an iterative process until both erosion was reduced and landscape volume optimised. The improved geomorphic rehabilitation shows high erosional stability, but would be expected to perform better if more design and modelling iterations would be performed. The SIBERIA modelling was critical for identifying four main causes of instability that were turned into stability by guaranteeing in subsequent designs: (a) appropriate concavity at any foothill transitioning towards the channels; (b) that runoff is always directed towards the swales (0-order subcatchments); (c) a correct design of catchments from the top of the landscape to streamline; (d) long term stability of the main valley (meandering) channels by constructing entire subcatchments.

The consideration of these factors in the GeoFluv designs produced successively lower erosion rates for each landscape iteration. As a main conclusion for the coalfields of the Hunter Valley, the Improved GeoFluv design using SIBERIA modelling reduced erosion by half while being able to store 7% more mine waste volume than contour banks. Additionally, the gullying pattern was predicted by the landscape evolution model and 77% of the eroded material was predicted to be deposited within the first-order subcatchments, further reducing significantly sediment yield.

Additionally, while not being the main purpose of the research, a CAD-based procedure has been developed to extract the natural contouring (NC) of undisturbed lands adjacent to mines (Drayton in this case) as a theoretical landform design alternative. This procedure has been strictly developed for scientific purposes, and authors do not recommend this landform approach be used as an alternative for mine rehabilitation without careful geomorphic assessment.

In conclusion, the joint use of geomorphic design software with a landscape evolution model showed complementary capabilities for optimised landform design. Through an iterative design process and landscape evolution modelling, optimised geomorphic designs can be reached. Supplementary to this research, compared assessments between geomorphic and traditional landform designs using economic, hydrologic, ecologic and visual issues should provide both the mining industry and regulators with improved rationale for decision making. This is important, as the public is demanding much higher standards of mine rehabilitation.

Acknowledgements

This paper is the outcome of a joint research of the three authors, made possible by means of a research stay of J.F. Martín Duque, hosted by G.R. Hancock and G.R. Willgoose, at the University of Newcastle (UoN, Australia). This stay has been funded within a program *Estancias de Movilidad de Profesores e Investigadores en Centros Extranjeros de Enseñanza Superior* of the Spanish Minister of Education, Culture and Sports (reference PRX16/00441). The authors acknowledge the kind collaboration of the Tom Farrell Institute for the Environment of the UoN. Drayton (AngloAmerican) has kindly supported this research, by providing the GeoFluv-as-built topography, along with all the needed information, which main aim has been getting knowledge in order to develop best mine rehabilitation practises. The assistance of Matt Lord and team is highly appreciated. This manuscript is also a contribution under the joint research of the Ecological Restoration Network REMEDINAL-3 of the Madrid Community (S2013/MAE-2719). Nicholas Bugosh also provided useful information and comments. Finally, two anonymous reviewers and Francis Rengers made very constructive comments at the review process.

References

Ahnert, F., 1976. Brief description of a comprehensive three-dimensional model of landform development. Z. Geomorphol Supplement Band. 25, 29–49.
Blanco, H., Lal, R., 2008. Principles of Soil Conservation and Management. Springer, Heidelberg.
Bugosh, N., 2000. Fluvial Geomorphic Principles Applied to Mined Land Reclamation at January OSM Alternatives to Gradient Terraces Workshop. Farmington, NM.
Bugosh, N., 2003. Innovative Reclamation Techniques at San Juan Coal Company (or why we are doing our reclamation differently). In: July Rocky Mountain Coal Mining Institute National Meeting. Copper Mt., Colorado.
Bugosh, N., Eckels, R., 2006. Restoring erosional features in the desert. Coal Age 111 (3), 30–32.
Bugosh, N., Epp, E., 2015. Evaluating sediment production from native and fluvial geomorphic reclamation watersheds at La Plata mine and its relationship to local precipitation events. In: NAAMLP 37th Annual Conference, Santa Fe.
Bugosh, N., Martin Duque, J.F., Eckels, R., 2016. The GeoFluv method for mining reclamation: why and how it is applicable to closure plans in Chile. In: Wiertz, J., Priscu, D. (Eds.), Planning for Closure 2016, First International Congress on Planning for Closure of Mining Operations, Gecamin, Santiago of Chile, pp. 8.
Bui, E.N., Hancock, G.J., Wilkinson, S.N., 2011. Tolerable hillslope soil erosion rates in Australia: linking science and policy. Agric. Ecosyst. Environ. 144, 136–149.
Carlson software, 2017. The Carlson Software Website. http://www.carlsonsw.com/, Accessed date: 22 October 2017.
Cohen, S., Willgoose, G.R., Hancock, G., 2009. The mARM spatially distributed soil evolution model: a computationally efficient modelling framework and analysis of hillslope soil surface organization. J. Geophys. Res. 114, F03001.
Coulthard, T.J., Hancock, G.R., Lowry, J.B.C., 2012. Modelling soil erosion with a downscaled landscape evolution model. Earth Surf. Process. Landforms 37, 1046–1055.
Environment Australia, 1998. Landform Design for Rehabilitation. Department of the Environment, Canberra.
Evans, K.G., Riley, S.J., 1994. Planning stable post-mining landforms: the application of erosion modelling. In: Proceedings of the AusIMM Annual Conference, Darwin NT, Parkville, pp. 411–414.

Evans, K.G., Loch, R.J., 1996. Using the RUSLE to identify factors controlling erosion rates of mine soils. Land Degrad. Dev. 7, 267–277.
Flanagan, D.C., Livingston, S.J., 1995. Water erosion prediction project (WEPP) version 95.7 user summary. In: Flanagan, D.C., Livingston, S.J. (Eds.), 'WEPP User Summary', NSERL Report No 11, July 1995.
Génie Géologique, 2017. The Talus Royal Method Website. http://www.2g.fr/, Accessed date: 22 October 2017.
Goodman, J.M., Haigh, M.J., 1981. Slope evolution on abandoned spoil banks in Eastern Oklahoma. Phys. Geogr. 2 (2), 160–173.
Gyasi-Agyei, Y., Willgoose, G.R., 1996. Evaluation of the use of contour banks as a post-mining rehabilitation control option using a digital terrain based rainfall runoff erosion model. In: Holzman, H., Nachtnebel, H.P. (Eds.), Application of Geographic Information Systems in Hydrology and Water Resources Management, HydroGIS '96, Vienna, Austria, 16–19 April 1996, pp. 143–150.
Haigh, M.J., 1979. Ground retreat and slope evolution on regraded surface-mine dumps, Waunafon. Gwent. Earth Surf. Process. 4 (2), 183–189.
Haigh, M.J., 1980. Slope retreat and gullying on revegetated surface mine dumps, Waun Hoscyn, Gwent. Earth Surf. Process. 5 (1), 77–79.
Haigh, M.J., 1985. The experimental examination of hill-slope evolution and the reclamation of land disturbed by coal mining. In: Johnson, J.H. (Ed.), Geography Applied to Practical Problems. Geo Books, Norwich, pp. 123–138.
Haigh, M.J., 1992. Problems in the reclamation of coal-mine disturbed lands in Wales. International Int. J. Surf. Min. Reclamat. Environ. 6 (1), 31–37.
Hahn, D.T., Moldenhauer, W.C., Roth, C.B., 1985. Slope gradient effects on erosion of reclaimed soil. Transactions of the ASABE 28 (3), 0805–0808.
Hannan, J.C., 1984. Mine Rehabilitation. A Handbook for the Coal Mining Industry. New South Wales Coal Association, Sydney.
Hancock, G., 2004. The use of landscape evolution models in mining rehabilitation design. Environ. Geol. 46, 561–573.
Hancock, G.R., Willgoose, G.R., Evans, K.G., Moliere, D.R., Saynor, M.J., 2000. Medium term erosion simulation of an abandoned mine site using the SIBERIA landscape evolution model. Aust. J. Soil Res. 38, 249–263.
Hancock, G.R., Loch, R.J., Willgoose, G.R., 2003. The design of postmining landscapes using geomorphic principles. Earth Surf. Process. Landforms 28, 1097–1110.
Hancock, G.R., Crawter, D., Fityus, S.G., Chandler, J., Wells, T., 2008. The measurement and modelling of rill erosion at angle of repose slopes in mine spoil. Earth Surf. Process. Landforms 33, 1006–1020.
Hancock, G.R., Lowry, J.B.C., Coulthard, T.J., Evans, K.G., Moliere, D.R., 2010. A catchment scale evaluation of the SIBERIA and CAESAR landscape evolution models. Earth Surf. Process. Landforms 35, 863–875.
Hancock, G.R., Willgoose, G.R., Lowry, J., 2013. Transient landscapes: gully development and evolution using a landscape evolution model. Stoch. Environ. Res. Risk Assess. 28 (1), 83–98.
Hancock, G.R., Coulthard, T.J., Lowry, J.B.C., 2016. Predicting uncertainty in sediment transport and landscape evolution – the influence of initial surface conditions. Comput. Geosci. 90, 117–130.
Hancock, G.R., Willgoose, G.R., 2017. Sustainable mine rehabilitation – 25 Years of the SIBERIA landform evolution and long-term erosion model. In: AusIMM, from Start to Finish: Life-of-mine Perspective. Australian Institute of Mining and Metallurgy, pp. 371–381.
Hazelton, P., Murphy, B., 2007. Interpreting Soil Test Results. What Do All the Numbers Mean? CSIRO Publishing, Collingwood.
Ibbitt, R.P., Willgoose, G.R., Duncan, M.J., 1999. Channel network simulation models compared with data from the Ashley River, New Zealand. Water Resour. Res. 35 (12), 3875–3890.
JRC, 2018. Best Available Techniques Reference Document for the Management of Waste from the Extractive Industries in Accordance with 839 Directive 2006/21/EC. Joint Research Centre, European Commission 840 (Final Draft, September 2018).
Kelder, I., Waygood, C., 2016. Integrating the use of natural analogues and erosion modelling. In: Fourie, A., Tibbett, M. (Eds.), Landform Design for Closure, in: Mine Closure 2016 –Australian Centre for Geomechanics, Perth.
Kirkby, M.S., 1971. Hillslope Process-response Models Based on the Continuity Equation, Slopes: Form and Process, Serial Publication 3. Institute of British Geographers, pp. 15–30.
Landloch Ptd Ltd, 2010. Preliminary Report. Sustainable Landscape Design for Coal Mine Rehabilitation. Project No 18024. Report Prepared for ACARP.
Leopold, L.B., Wolman, M.G., 1960. River meanders. Geol. Soc. Am. Bull. 71, 769–794.
Martín-Moreno, C., 2013. Cuantificación de la producción de sedimentos en la zona minera del Parque Natural del Alto Tajo. PhD Dissertation. Complutense University, Madrid.
Martín-Moreno, C., Martín Duque, J.F., Nicolau, J.M., Muñoz, A., Zapico, I., 2018. Waste dump erosional landform stability – a critical issue for mountain mining. Earth Surf. Process. Landforms 43, 1431–1450.
Martín Duque, J.F., Bugosh, N., 2014. Examples of Geomorphic reclamation on mined lands in Spain. From pioneering cases to the use of the GeoFluv method. In: 2014 OSM National Technical Forum: Advances in Geomorphic Reclamation at Coal Mines, Albuquerque, New Mexico, May 20-22, Office of Surface Mining, Reclamation and Reinforcement (OSM). Department of Interior, United States.
Martín Duque, J.F., Zapico, I., Oyarzun, R., López García, J.A., Cubas, P., 2015. A descriptive and quantitative approach regarding erosion and development of landforms on abandoned mine tailings: new insights and environmental implications from SE Spain. Geomorphology 239, 1–16.
Martinez, C., Hancock, G.R., Kalma, J., 2009. Comparison of fallout radionuclide (caesium-137) and modelling approaches for the assessment of soil erosion rates for an uncultivated site in southeastern Australia. Geoderma 151, 128–140.
RIVERMorph, 2017. Rivermorph Software. http://www.rivermorph.com/, Accessed date: 22 October 2017.
Rosgen, D.L., 1994. A classification of natural rivers. Catena 22, 169–199.
Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs.
Sawatsky, L., Beckstead, G., 1996. Geomorphic approach for design of sustainable drainage systems for mineland reclamation. Int. J. Surf. Min. Reclamat. Environ. 10 (3), 127–129.
Sawatsky, L., McKenna, G., Keys, M.J., Long, D., 2000. Towards minimizing the long-term liability of reclaimed mined sites. In: Haigh, M.,J. (Ed.), Reclaimed Land: Erosion Control, Soils and Ecology. Balkema, Rotterdam, pp. 21–36.
Sears, A.E., Bise, C.J., Quaranta, J.D., Hopkinson, L.C., 2014. Field and modelling study for stream mitigation on surface mine sites in West Virginia. Min. Eng. 66 (5), 48–53.
Sheridan, G.J., So, H.B., Loch, R.J., Pocknee, C., Walker, C.M., 2000. Use of laboratory scale rill and interrill erodibility measurements for the prediction of hillslope–scale erosion on rehabilitated coal mines soils and overburden. Aust. J. Soil Res. 38 (2), 285–298.
SMCRA, 1977. Surface Mining Control and Reclamation Act. Public Law, 95–87, Statutes at Large, 91 Stat. 445. Federal Law, United States.
Stiller, D.M., Zimpfer, G.L., Bishop, M., 1980. Application of geomorphic principles to surface mine reclamation in the semiarid West. J. Soil Water Conserv. 274–277.
Toy, T.J., Chuse, W.R., 2005. Topographic reconstruction: a geomorphic approach. Ecol. Eng. 24, 29–35.
Tucker, G., Hancock, G.R., 2010. Modelling landscape evolution. Earth Surf. Process. Landforms 35, 28–50.
Waygood, C., 2014. Adaptative landform design for closure. In: Weiersbye (Ed.), Mine Closure 2014. University of the Witwatersrand, Johannesburg, pp. 12.
Welivitiya, W.D.P., Willgoose, G.R., Hancock, G.R., Cohen, S., 2016. Exploring the sensitivity on a soil area-slope-grading relationship to changes in process parameters using a pedogenesis model. Earth Surf. Dyn. 4, 607–625.
Welsh, D., Hinz, R., Garlipp, D., Gillespie, N., 1994. Coal mines on target with environmental planning. Queensl. Govern. Min. J. 94, 19–22.
Williams, D., 2000. Assessment of embankment parameters. In: Hustrulid, W.A., McCarter, M.K., Van Zyl, D.J.A. (Eds.), Slope Stability in Surface Mining. SME - Society for Mining, Metallurgy and Exploration, Littleton, pp. 275–284.
Williams, G.P., 1986. River meanders and channel size. J. Hydrol. 88, 147–164.
Willgoose, G.R., 1989. A Physically Based Channel Network and Catchment Evolution Model. PhD Dissertation. MIT.
Willgoose, G.R., 2001. Erosion processes, catchment elevations and landform evolution modelling. In: Mosley, P. (Ed.), Gravel Bed Rivers 2000. The Hydrology Society, Christchurch, pp. 507–530.
Willgoose, G.R., 2005. Mathematical modeling of whole-landscape evolution. Annu. Rev. Earth Planet Sci. 33, 443–459.
Willgoose, G.R., 2012. User Manual for SIBERIA, Version 8.33 (Online). pp. 115. Available from: http://www.telluricresearch.com/siberia_8.33_manual.pdf.
Willgoose, G.R., 2018. Principles of Soilscape and Landscape Evolution. Cambridge University Press, Cambridge.
Willgoose, G.R., Riley, S., 1998. The long-term stability of engineered landforms of the Ranger Uranium Mine, Northern Territory, Australia: application of a catchment evolution model. Earth Surf. Process. Landforms 23 (3), 237–259.
Willgoose, G.R., Sharmeen, S., 2006. A one-dimensional model for simulating armouring and erosion on hillslopes. 1. Model development and event-scale dynamics. Earth Surf. Process. Landforms 31 (8), 970–991.
Willgoose, G.R., Bras, R.L., Rodriguez-Iturbe, I., 1991a. A physically based coupled network growth and hillslope evolution model: 1 Theory. Water Resour. Res. 27 (7), 1671–1684.
Willgoose, G.R., Bras, R.L., Rodriguez-Iturbe, I., 1991b. A physically based coupled network growth and hillslope evolution model: 2 applications. Water Resour. Res. 27 (7), 1685–1696.
Willgoose, G.R., Bras, R.L., Rodriguez-Iturbe, I., 1991c. A physical explanation of an observed link area-slope relationship. Water Resour. Res. 27 (7), 1697–1702.
Willgoose, G.R., Bras, R.L., Rodriguez-Iturbe, I., 1991d. Results from a new model of river basin evolution. Earth Surf. Process. Landforms 16, 237–254.
Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses: a Guide to Conservation Planning. US. Department of Agriculture Handbook No. 537. US Government Printing Office, Washington DC.
Zapico, I., Martín Duque, J.F., Bugosh, N., Laronne, J.B., Ortega, A., Molina, A., Martín-Moreno, C., Nicolau, N., Sánchez, L., 2018. Geomorphic Reclamation for reestablishment of landform stability at a watershed scale in mined sites: the Alto Tajo Natural Park, Spain. Ecol. Eng. 111, 100–116.