LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **14**: 215–226 (2003)

Published online 3 February 2003 in Wiley InterScience (www.interscience.wiley.com). **DOI**: 10.1002/ldr.548

TRENDS IN RELIEF DESIGN AND CONSTRUCTION IN OPENCAST MINING RECLAMATION

J.-M. NICOLAU*

Departamento Interuniversitario de Ecología, Universidad de Alcalá de Henares, Madrid, Spain

Received 20 August 2002; Revised 20 November 2002; Accepted 5 December 2002

ABSTRACT

This paper examines trends in topography design and construction in opencast mining restoration. The greatest geomorphological focus is the protection of aquatic ecosystems downstream of reclaimed sites through the construction of topographies and structures that not only reduce sediments and contaminants to a minimum, but which soften the impact of maximum water flows. From the ecological point of view, the most important focus is the integration of the geomorphological component with those of the soil and vegetation, and the formation of a functional ecosystem with the capacity to maintain itself. The conceptual models of relief that have been used in practice are discussed and criticized: these include the platform-bank model (geotechnically but not ecologically stable), faithful reproduction of the original topography (inadequate in steep areas), and understanding the hydrological basin as a restoration unit (now considered the most appropriate). Finally, erosion models are reviewed as tools for relief design. The practicality of '*RUSLE 1·06 for Mined Lands, Construction Sites and Reclaimed Lands*' is underlined owing to its ease of use. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: topographic reconstruction; soil erosion; RUSLE model; SIBERIA model; mining reclamation; ecological restoration

INTRODUCTION

In the reclamation of ecosystems affected by earth movements, the final result is primarily conditioned by topographic reconstruction (Toy and Hadley, 1987). Many restoration projects have failed because topography designs have been unable to sustain functional ecosystems, and/or because of the exportation of runoff and sediments that have seriously damaged ecosystems downstream.

Giving form to relief design is without doubt the most expensive part of any mining reclamation project. Guaranteeing long-term stability is therefore a priority objective from both ecological and mining engineering points of view (Evans, in a unpublished doctoral thesis, 1997). In recent years there have been notable conceptual advances in the understanding of the hydrological and geomorphological responses of reclaimed relief forms. These have provided more solid criteria for relief design and have allowed the development of specific erosion models.

The aim of this work is to review the current trends and future perspectives of relief design in mining reclamation. The first section analyses the two main approaches to topographic reconstruction: the more geomorphological (which places emphasis on the off-site effects of erosion), and the more ecological (more centred on on-site effects). The second section criticizes the models or types of landscape reliefs that have been used: the platform-bank model, the original relief imitation model and the hydrological basins model. The third section is a review of the main erosion models developed specifically for use in mining restoration.

*Correspondence to: J.-M. Nicolau, Departamento Interuniversitario de Ecología, Universidad de Alcalá, 28871 Alcalá de Henares, Madrid, Spain. E-mail: josem.nicolau@uah.es

APPROACHES TO TOPOGRAPHIC DESIGN

The design of ever-more stable reliefs is pursued from two different—though not exclusive—directions. Relief can be designed with the idea of maximizing the viability of the ecosystem to be restored (*on-site effects*). This considers relief as a compartment of the ecosystem to be integrated with the soil and the plant community as part of the process of producing a functional system.

In the second approach, the relief must export the smallest possible quantity of runoff and sediments to water bodies downstream. The idea is to avoid any effect on aquatic populations (*off-site effects*) and to conserve basic ecosystem services related to water quality (Ehrenfeld, 2000). This approach is the most common. It is also the most developed, both conceptually and methodologically.

Relief design has been basically steered towards the second approach in some countries, there are laws protecting ecosystems downstream of areas altered by mining or construction activities (e.g. the Clean Water Act and the Surface Mining Control and Reclamation Act (SMCRA) in the United States. Often, this implies the reconstruction of an on-site functional ecosystem.

Relief Design with the Aim of Minimizing Runoff and Sediment Export to Downstream Ecosystems (Off-site Effects)

The most important advances in this area have been those of the Australian research team that developed the SIBERIA model (Willgoose and Riley, 1994, 1998) of the Canadian team whose work examined the reproduction of the environment's natural landscape (Sawatski *et al.*, 2000; Bender *et al.*, 2000), and the most classic approach based on the use of universal soil loss equation (USLE) and its derived models commercialized by the International Erosion Control Association (Fifield, 1994).

The methodology of the latter association not only centres on the design of stable relief forms, but also on the design and construction of safety structures that guarantee the non-emission of sediments and contaminants from restored sites to watercourses during times of maximum rainfall, in particular torrential events. Topographical reconstruction forms part of the association's Erosion and Sediment Control Plans. A good example of these plans is the technology developed and commercialized by Fifield (1994) in the form of computer software. An ideal erosion control plan would involve the following steps:

(1) Establishing the quantity of sediments that will be transported to natural watercourses from the sediment retained: sediment produced ratio (*performance standard*).
(2) Designing the topography and estimating the volume of runoff and quantity of sediments a site will produce at torrential events. Predictions are made using the *Sediment Yield Equation*, which combines the modified universal soil loss equation (MUSLE) erosion model and the number of curve hydrological model.
(3) Determining the effectiveness of complementary erosion control methods (the percentage of sediments that should be controlled by erosion control structures).
(4) Establishing the dimensions of the sedimentation control structures.

Structural measures of sedimentation control include sediment traps, bales of straw, gravel filters, check-dam structures and filter fences.

Sawatski *et al.* (2000) indicate that the aim of any restoration project is to reduce long-term risks (*long-term liability*) to zero. These risks include:

(1) Low productivity of the soil.
(2) Effects on water quality: acid drainage, heavy metals.
(3) Catastrophic destruction of the reclaimed relief: geotechnical instability of waste tips, breakage of dams etc.
(4) Intense water erosion.

The methodology they propose for constructing relief with acceptable sediment exportation levels is based on the comparative analysis of natural basins in the area, and consists of four steps:

(1) Establishment of the maximum sedimentation export rate for the basin to be reclaimed, using the available registries of the natural basins of the area.
(2) Establishment of sustainability criteria of the reclaimed relief in terms of runoff characteristics, erosion rates and ecosystem sustaining capacity. These are determined from the traits of the surrounding natural landscape such as topography and the drainage density of the different soil types.
(3) Establishment of functional criteria for the natural watercourses that drain the runoff away, mainly with respect to the flow regime at torrential events.
(4) Establishment of the characteristics of the aquatic habits to be protected: sediment concentration, spawning areas, feeding areas, etc.

In this case the reclamation site extends beyond the area originally degraded as far as those aquatic ecosystems likely to be affected.

The SIBERIA model points to the conclusion that without adequate topographical design, mining activities can cause severe environmental problems—the pollution of watercourses through the erosion of restored relief included. Consequently, an objective of topography design is to minimize environmental impact (Evans, 2000). Topographic restoration involves three steps:

(1) The design of a stable relief morphology using the SIBERIA topographic development model.
(2) Estimation of the transmissibility of sediments from the designed relief to natural basins and watercourses using a sedimentation prediction model such as revised universal soil loss equation (RUSLE) or water erosion prediction project (WEPP).
(3) Evaluation of the changes in water quality in natural watercourses using a hydrological model that predicts flow and estimates sediment concentration from data supplied by the erosion model.

The SIBERIA model is explained further in the final section on ‘Erosion models in relief design’.

Relief as a Compartment to be Integrated with Soil and Vegetation in the Construction of a Functional Ecosystem (On-site Effects)

As well as the above essentially geomorphological approach, there is another, more ecological, in which reclamation is directed towards integration of the relief with the soil and vegetation for the construction of functional ecosystems. From this more ecological perspective, to restore is to generate functional ecosystems, i.e. those which have the capacity for self-maintenance and which connect with the ecosystems around them (Carpenter, 1998). For this to be achieved, topography, soil and vegetation are manipulated together to optimize the restitution of key ecological processes. Several authors affirm that the soil is the key component in achieving a sustainable restored ecosystem (Palmer, 1992; Beeby, 1993): a biologically functional soil with appropriate levels of organic matter and nitrogen, with positive mineralization rates derived from microbial activity (Bradshaw, 1988) and preferrably a mesofauna food web with worms as indicators.

However, the geomorphological component notably influences the self-maintenance of restored ecosystems since it is key in the supply of water to plants and determines the intensity of erosion (an abiotic exploitation mechanism that holds back ecological succession [Margalef, 1968]). Several authors have mentioned the effects of erosion on the vegetation of reclaimed slopes, especially during the establishment of herbaceous vegetation. Kapolka and Dollhopf (2001) affirm that one of the most important concerns with respect to steep slope reclamation is soil erosion since soil loss can have a negative effect on plant establishment. Loch (1997) indicates that, in environments which suffer erosive precipitation, plant growth and rainfall erosion risk are closely linked. This means there is less opportunity for vegetation to become established in non-erosive periods, increasing the need for special approaches to minimize the risk of major erosion. Haigh (1992) alludes to accelerated erosion as one of the factors causing the progressive deterioration of reclaimed grasslands in Welsh coalfields. In this case, the mechanism is connected to the weathering of shale and the formation of an impermeable layer in the soil at a depth of 30 cm. In Mediterranean–continental environments, the water deficit—which is the main limiting factor for plants and mesofauna—is frequently associated with intense water erosion of the soil surface (Nicolau and

Asensio, 2000). A positive feedback interaction is set up between these phenomena, and as a consequence of erosion there is a decrease in water availability. This can be caused by a decrease in soil depth (diminishing water storage capacity) and by crusting of the surface (reducing infiltration capacity) of soils with low plant cover (Pimentel and Harvey, 1999).

The reduction in water availability to plants is not the only mechanism by which water erosion exercises abiotic exploitation of ecosystems; it also extracts nutrients, biological propagules and the substratum (Young, 1992) affecting the productivity (Margalef, 1970). Torrential rainfall events in early phases of reclamation process can modify soil conditions for water and nutrients supply to plants. As these events are unpredictable, soil erosion can be seen as a process that contributes to the stochasticity of the ecological succession.

In synthesis, the search for the capacity of self-maintenance in ecosystems reclaimed in opencast mining areas is based on the design of stable relief forms, biologically functional soil and productive plant and mesofauna communities with an active nutrient succession cycle, and the long-term self-replacement of species. The reconstruction of relief must be integrated with these other components to optimize the supply of water and nutrients, to control the abiotic exploitation of erosion and to favour the heterogeneity of habitats.

Even so, there is still no complete protocol for the integrated design of ecosystems which uses the models that formalize key interactions and predict ecosystem stability. A first approximation was attempted in the Teruel coalfield in Spain (Minas y Ferrocarril de Utrillas, SA, 2001; Nicolau, 2001), where the design of a slope restoration protocol that favoured plant development over erosion involved the following phases: (1) tuning of the RUSLE 1·06 model to allow estimation of the erosion rate, (2) determination of the maximum tolerable erosion rate for the plant community and (3) the use of RUSLE 1·06 to determine the magnitude of the macro- (LS) and microtopography (ridge height) and selection of the substratum with an erosion rate below threshold. The weakest point was the assignation of a value of maximum tolerable erosion, which was established from expert opinion. This approximation, though doubtless of practical use, had important conceptual flaws. Other, more ecological models—that assume non-linear relationships between vegetation and erosion and incorporate feedback systems between them—must be developed (Puigdefábregas, 1996; Weltz *et al.*, 1998).

CONCEPTUAL MODELS OF ARTIFICIAL RELIEF

Relief types have developed from models orientated exclusively towards geotechnical stability to those orientated towards ecological stability. This section sets out the geomorphological basis of artificial relief design and looks at the practical difficulties encountered in this and relief construction. An analyses is also made of the three most commonly used relief models.

Basic Principles in the Construction of Relief Forms

The major theoretical contributions—from geomorphology to relief from design—have been those of Professor T. Toy, and these are collected in the now-classic *Geomorphology of Disturbed Lands* (Toy and Hadley, 1987). Within the deterministic paradigm, Toy postulates that the objective is to reestablish a balance between forms and processes. In turn, this implies an equilibrium between erosive forces that act at the soil surface (water flow) and the resistance forces presented by the soil (structural resistance of soil materials, cohesiveness of surface deposits and the effects of vegetation). Obviously, to reach a balance in reclaimed ecosystems, time has to pass in order that an effective plant cover and root network be generated, so that an edaphic structure can be developed, and so that the forms of slopes and channels can adjust.

From a more applied standpoint, Toy and Black (2000) propose the following general objectives in topographical reconstruction:

- The creation of stable platforms that are not subject to mass movement.
- Water management that controls erosion and favours the development of vegetation. In wet regions this would require the control of external (*runon*) and internal (*runoff*) water in the reclaimed area to regulate erosion and control water quality. In dry areas, water conservation practices would need to be optimized (relief forms that

collect and distribute water, manipulation of the surface to improve *in situ* infiltration, and mulching to reduce evaporation.

- Minimization of long-term maintenance costs.
- Favouring the heterogeneity of habitats for wildlife.

Factors Influencing Relief Construction

Among the several factors affecting relief construction is its high degree of dependence on the dynamics of the mining activity (the quantity and location of materials will depend on the rhythm of the mining operation), and the restrictions imposed by the climate and morphology of the original relief over which new ecosystems are built (Toy and Black, 2000).

The climate normally determines the restoration work calendar and influences choices of water and erosion management.

The economic cost of topographic reconstruction depends directly on the original topography. Gently rising surfaces might require the import of materials for infilling, while steep and irregular surfaces demand costly earth-moving operations.

With respect to surrounding ecosystems, the adjacent topography imposes further limiting conditions on the design. It often becomes the main feature affecting planning. Among other aspects, it influences the management both local and 'outside' waters that cross the reclamation site.

The Platform-bank Model

The aim of the first relief reclamation experiments was to achieve the geotechnical stability of reclaimed sites. With such stability it was hoped that mass movements—and potential accidents—would be avoided. This gave rise to a relief model for waste tips in the shape of a truncated pyramid with steep, rectilinear slopes (bank 30 degrees) and drainage ditches, all superimposed upon a natural landscape—the so-called platform-bank models shown in Figures 1 and 2. This immature topography is unable to sustain functional ecosystems and can support neither natural nor agricultural uses because of its scant ability to retain water and the intense surface water erosion it suffers. In addition, such topography gives rise to high runoff rates and sediment which affect natural watercourses and produce adverse environmental impacts. Therefore, while geotechnically stable, this topography

Figure 1. Pyramidal topography corresponding to the platform-bank model on a flat original relief.

Figure 2. Filled-valley following the platform-bank model.

is not ecologically stable. Later, this model was further developed by reducing the angle of the slopes and incorporating substrates that favoured plant development. Even though the design has severe, fundamental limitations and is now conceptually obsolete, it is still widely used.

Forms such as these that are far from equilibrium tend towards it through intense erosion, especially via rill formation (on slopes with compact surfaces and little plant cover, the erosion rate might reach $507\,t\,ha^{-1}\,y^{-1}$ [Porta *et al.*, 1989]), the formation of gullies owing to deficiencies in the functioning of berms and terraces during maximum rainfall events (Sawatski *et al.*, 2000) and intense laminar erosion (Sánchez and Wood, 1989). Erosion is more weathering-limited than transport-limited (Haigh, 1985).

Original Relief Imitation

The American mine restoration legislation of 1977 SMCRA is inclined towards the restoration of original topography. This position, however, is not shared by the majority of the scientific community according to Toy and Black (2000). Brenner (1985) points out that the slopes resulting from attempts to copy the originals are often excessively long and compacted by the movement of machinery. Revegetation is therefore difficult and the stability of the non-consolidated materials is not the same as the original. Bell *et al.* (1989) reported instability through intense erosion because of the lack of equilibrium between relief forms and the consistency of the materials used in the Appalachians, reporting that such practices were not recommendable on steep slopes.

The Hydrological Basin as a Relief Restoration Unit

The approach to relief design with the best scientific basis is that which, based upon geomorphic and hydrological principles, understands the hydrological basin as a natural unit of artificial relief construction (Figures 3 and 4). Relief is organized on the basis of individual hydrological basins composed of slopes and watercourses, and with safety structures to prevent destruction during times of extreme rainfall. The main elements to be managed are the surface of the basin, the density and pattern of the drainage network, the morphology of the slopes and channels, and the structural measures for controlling runoff and sediments (sediment traps, regulatory ponds, watercourse protection systems, etc.).

For the construction of mature reliefs with natural functional dynamics, two approaches have been attempted. The first is the comparative study of the surrounding natural landscapes to determine the ranges of slope, length

Figure 3. Constructed hydrological basin composed of slopes (both, gentle and steep), a wide platform, water channels and small wetlands for water flow regulation.

Figure 4. Constructed hydrological basin on a steep original relief. Artificial slopes still follow the platform-bank model. Reservoir works as a firebreaks line avoiding sediment emission to the natural watercourses and reducing peakflows.

and convexity in which natural reliefs remain stable, in order to copy them and their drainage patterns and so on. The hydrological and erosive characteristics of the new landscape will be similar. This can be achieved if natural soils can be restored and revegetation is rapid. One of the most careful studies in this respect was that undertaken by Riley (1995) in tropical Australia, which attempted to guarantee maximum relief stability in a uranium mine restoration site. For safety's sake, a morphology was sought that would not allow gullies or rills to form.

The alternative, which is appropriate where soil and revegetation management do not allow the erosive and hydrological characteristics of the natural landscape to be reproduced, is to design a new relief with safety features that prevent the effects of extreme rainfall, especially during the first stages of succession when the soil and plant community are developing. The most common safety 'fire breaks' are ponds that act as sediment traps (Sawatski *et al.*, 2000). The stability of the relief is confirmed by hydrological and erosion models.

Slopes

For Sawatski, a mature topography is one which is characterized by relatively short banks with ever-more gentle slopes that concentrate runoff. It should also concentrate on well-defined courses sufficiently deep to evacuate maximum water flows. Instead of uniform banks, mature topographies should have heterogeneous slopes with hills and valleys which, in addition to the aesthetic improvement they bring, provide a wider variety of habitats for fauna and avoid the high runoff rate so typical of straight, long slopes.

The work of Haigh (1979, 1980, 1985) on the development of artificial slopes was important for establishing design criteria. Haigh identified the sigmoid profile (convex–straight–concave) as the most stable, found a significant influence of orientation—but not vegetation—on the development of the profile, and identified the dynamics of the slope bottom as an important control factor (deposition or erosion, the latter frequently caused by ditches).

The hydrological response of reclaimed slopes in Mediterranean–continental environments has been described by Nicolau (2002), who characterized the biotic and abiotic controls of runoff generation and surface flow on topsoiled and overburden-covered slopes. On topsoil-covered slopes, grass communities play an important hydrological role, enhancing soil infiltration capacity and providing a more homogeneous response over the year compared to that of overburden. Spatial runoff connectivity between interrill areas and the catchment outlet is very low and is controlled mainly by the magnitude of rainfall and soil moisture. The hydrological response of topsoil substratum is compatible with vegetation development. Overburden substratum develops a superficial crust that greatly reduces infiltration capacity, leading to dense rill networks. Runoff routing along the slope depends on spatial and seasonal variation of soil crust in interrill areas where reinfiltration takes place. The very intensive sheet and rill erosion, as well as scant water availability in the soil, prevent plant colonization.

Osterkamp and Joseph (2000) warn of differences in the water flow depending upon the degree of concavity–convexity of slopes: convergent on concave slopes, parallel on straight slopes and divergent on convex slopes. The practical implications for construction are explained by Toy and Black (2000), who indicate that concave slopes at basin heads and convex slopes are more difficult to construct than straight slopes because of the greater manoeuvring problems of earth-moving machinery. Concave slopes at basin heads require careful control of runoff and subsurface discharge, and convex slopes are more unstable than straight slopes. Convex slopes, since they disperse the water flow, are the driest. Finally, these authors indicate the need to bear in mind the types of vertical movement suffered by the materials making up artificial reliefs, i.e. settling (caused by the extinction of empty spaces between particles owing to compression) and subsidence (caused by the eluviation of small particles towards pores of greater size between large particles).

Water Channels

The construction of water channels is inspired less in the available knowledge of natural systems than in engineering principles. Normally, construction is undertaken following engineering rather then geomorphological criteria. Water channels serve to transport surface water from one point to another without causing excessive erosion or harm downstream, and to minimize the saturation of materials underneath in order to avoid floods. They must therefore imitate natural morphology with respect to depth, slope, width, sinuosity and meander wavelength (Stiller *et al.*, 1980), and should incorporate buried rock and flood plains to attenuate the effects of floods.

Sawatski *et al.* (2000) have proposed the 'passive channel erosion protection measures' for a suitable configuration of the landforms at mine-disturbed land. This is accomplished without structural systems such as riprap, drop structures or rigid linings. It includes measures whereby the size of drainage basins is controlled to avoid large discharges in a single channel on a steep slope. The use of cohesive soils mixed with gravel and cobbles beneath drainage courses provides for stream channel armouring and rearmouring in the event of large floods. Some examples of passive erosion protection measures are as follows: floodplains to attenuate flows (flow velocities and peak flow); bouldery ground beneath drainage channels (placement of waste rock or overburden material with high rock content beneath a drainage channel, which introduces a self-healing capability); suitable drainage density; use of regime channels by selecting the appropriate parameters (channel depth, slope, width, sinuosity, meander wave length and width to depth ratio) in order to suit the required overall valley gradient and bed/bank materials. The resultant drainage systems, based on passive erosion control measures, will offer superior performance in the long run. The costs of such systems are not necessarily greater than the cost of conventional structural systems.

A very interesting view is given by Mutz *et al.* (2002) who have studied the undirected development of streams in reclaimed opencast coal mining in Lusatia, Germany. They point out that there is a complex control on the streams evolution. This is constrained by such abiotic factors as water chemistry and bed sediments, hydrology, valley morphology and channel pattern as well as by biotic processes such as plant growth and the rate of organic matter decomposition. As a consequence of this complexity, two points can be remarked in relation to channels design. On the one hand, there is the uncertainty about the outcome of the undirected development of streams and the sustainable state of managed post-mining streams. On the other hand, there is the very active interaction between biotic processes occurring through the ecological succession and the geomorphic evolution of watercourses. A good example of this concerns the pattern of plant colonization and the litter decomposition. They strongly condition stream evolution and, at the same time, both processes are initially controlled by abiotic factors like water chemistry and water-holding capacity of the bank soils (Siefert and Mutz, 2001). Sure enough, water acidity limits colonization of aquatic life and hinders the decay of organic matter, and low water-holding capacity of the bank soils only allows colonization of species adapted to dry soils. The degree of plant colonization determines shaded and non-shaded streams. Low organic matter decomposition rates lead to accumulation of leaves and dead wood in the beds which produces partial blockage of the channels in the shaded streams. So, wide and shallow stream channels with high structural diversity seem probable in shaded streams. In non-shaded watercourses only few species are able to be settled. These tend to grow from the channel margin to the centre. They can block portions of the channel and force the thread of flow to a small line in the centre of the cross-section.

EROSION MODELS IN RELIEF DESIGN

With respect to mining reclamation, Evans (unpublished thesis, 1997) affirms that '*to successfully incorporate the design of relief forms, the stability of the final forms must be predicted, which implies the use of hydrological and erosion models*.'

In recent years, some erosion models for reclaimed areas have been developed which are now being used in relief design. The RUSLE 1·06 (for mined lands, construction sites and reclaimed lands) is a model that estimates the annual surface erosion by water (Toy and Foster, 1998). It is derived from USLE and RUSLE and it was developed using empirical data gathered from mining and reclaimed soils. RUSLE retains the structure of its predecessor, the USLE, namely:

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

where A = annual soil loss, R = rainfall erosivity, K = soil erodibility, LS = length and slope angle, C = plant cover factor, P = soil conservation practices.

Although RUSLE 1·06 is still an empirical model it has notable modifications with respect to USLE. The K factor takes into account the variability of soil erodibility over the year. Both K and C factors now take into account the influence of stone fragments both on the surface and within the soil. The equations used to estimate the LS factor have been altered to improve their precision, and amplified to include steeper slopes than those considered by the USLE model. Factor C is determined from four subfactors which take into account the main characteristics of different soil surface coverings and their handling. The P value is now determined by new equations based on physical processes. The estimation of erosion of concave slopes is therefore now possible. With respect to both *P* and *C* factors, soil conservation techniques and the vegetation types of reclaimed mining areas are considered.

Kapolka and Dollhopf (2001) indicate the tendency of RUSLE 1·06 to underestimate the erosion rate on slopes with rills, and have developed a method for better estimating the *K* factor which considers the soil's susceptibility to rill formation. Abel *et al.* (2000) came to the same conclusion with respect to intensely rilled artificial slopes at German lignite mines. Nicolau (2001), in a Mediterranean–continental environment, notes its satisfactory predictive capacity except for slopes that develop rills, for which the model underestimates erosion rates. Others, such as Evans and Loch (1996), found good adjustment in experiments with artificial rainfall. Kelsey (2002) used RUSLE on an event-by-event basis with simulated rain and found overestimation of soil loss both for rill erosion (bare soil conditions) and sheet erosion (soil covered by blankets) in silty clay loam soils, and underestimation in Chetek sandy loam soils under bare soil conditions, although the differences were not significant.

Toy and Osterkamp (1995) analyse the applicability of the RUSLE to geomorphological studies and describe the advantages as: (1) simplicity, (2) the existing large database, (3) ease of obtaining parameters, (4) widely used by government agencies, (5) adaptable to uniform areas where there is no sedimentation. The disadvantages they mention are: (1) inability to estimate sedimentation, the production of sediments and erosion in channels and badlands, (2) lack of precision in estimates of soil loss for a single torrential event. Another serious limitation is the difficulty of incorporating new advances in research by calculating them as a product of factors.

Although limited from the conceptual point of the view, RUSLE 1·06 is the only specific model for reclaimed lands that is ready to be used worldwide by mining companies and agencies. It is accurate enough, except for rilled slopes, and user friendly, so it can be therefore recommended as a tool for relief design.

Willgoose and Riley (1994, 1998) developed the SIBERIA model. It is a physically based predictive model that can simulate the geomorphic evolution of landforms subjected to fluvial erosion and mass transport processes (Evans, unpublished doctoral thesis, 1997). SIBERIA links widely accepted hydrology and erosion models under the action of runoff and erosion over variable time scales. The sophistication of SIBERIA lies in its use of digital terrain models for the determination of drainage areas and geomorphology as well as its ability to efficiently adjust the landform with time in response to the erosion that occurs on it.

SIBERIA modelling has been based on parameters derived from experimental data from the current ERA Ranger Mine waste rock dump in Australia. Hancock *et al.* (2000) conclude that several studies have demonstrated that SIBERIA is validated for different landscapes examined—mine sites, natural catchments—and it provides a new tool for predicting erosion of post-mining landscapes. SIBERIA is still a scientific tool not used by the companies.

Also in Australia, a methodology has been developed for relief design in mining restorations that combines the curve number method for hydrology, RUSLE–MUSLE for sediments, and the GRASP model for herbaceous plant growth. It is specifically adressed to mining reclamation and it includes plant dynamics in an explicit way (Loch, 1997; Loch and Sell, 1998). This methodology has been developed with the cooperation of several universities, mining and environmental public administration and private mining companies working together in the project 'Post-mining Landscape Parameters for Erosion and Water Quality Control'. Computer packages have been developed as a means of both compiling the enormous amount of data obtained and of following it to be used in landform design and assessment by mining companies and agencies.

Other attempts to develop models that predict erosion in mining restorations have had little success. However, this is not so much because of any lack of precision. Rather, their complexity makes them difficult to use. An example is the model of Khanbilvardi and Rogowski (1986) based on USLE and produced for the Environmental Protection Agency (EPA). This is a sediment and transport model used to calculate erosion in each cell of a net which covers the drainage area and can go from a plot to a basin. It was carefully tested and the program is available from the authors. The model predicts the rules followed by sediments and the flow network as well as soil loss through the growth of rills and the contributing areas between the rills. It considers convex and concave areas, and takes vegetation into account but is not user friendly.

CONCLUSION

Relief production is the first step on which the success of any restoration project involving earth movement depends. The integration of topography with the soil and vegetation compartments is a requisite for reclaiming ecologically stable ecosystems, i.e. those with the ability to maintain themselves and that integrate with the surrounding environment, reducing off-site effects.

Knowledge of natural reliefs has allowed a conceptual model of relief (based on hydrological basins) to be developed, as well as tools for relief design and assessment (model of erosion and hydrology). RUSLE 1·06, in spite of its conceptual limitations, can be recommended to many companies and government agencies, because it offers sufficient guarantees of success predicting erosion in no-rilled slopes. Other methodologies—conceptually more advanced—developed in Australia show the new ways in this field in order to have more practical tools for relief design. However, at the theoretical level, there is still some way to go before we can integrate in an ecological way the three basic components of the system to be reclaimed. This is especially important for evaluating the response of restored ecosystems to extreme events (rain and/or drought).

In most of the countries relief is frequently fashioned according to the platform-bank model, and topographic design relies more on practical, *in situ* experience than the use of predictive models. This lack of modernization, both conceptual and technical, is one of the reasons for the numerous failures of opencast mining reclamation projects.

Indeed, the high number of failures is worrying. It is recommended that government authorities more carefully monitor the progress of restored ecosystems, and keep track of both biotic and abiotic variables. Further, society as whole needs to acquire a greater consciousness of the value of environmental goods and services that restoration aims to restore and conserve and that are vital to reach the level of well-being we wish to enjoy.

REFERENCES

Abel A, Michael A, Zartl A, Werner F. 2000. Impact of erosion-transported overburden dump materials on water quality in Lake Cospuden evolved from a former open cast lignite mine south of Leipzig, Germany. *Environmental Geology* **39**: 683–688.

Beeby A. 1993. *Applying Ecology.* Chapman & Hall: London.

Bell JC, Daniels WL, Zipper CE. 1989. The practice of approximate original contour in the Central Appalachians. I. slope stability and erosion potential. *Landscape Urban Planning* **18**: 127–138.

Bender MJ, Sawatski L, Long D, Anderson PG. 2000. A strategy for determining acceptable sediment yield for reclaimed mine lands. In *Reclaimed Land. Erosion Control, Soils and Ecology*, Haigh M (ed.). Balkema: Rotterdam; 37–50.

Bradshaw A. 1988. Alternative endpoints for reclamation. In *Rehabilitating Damaged Ecosystems*, Cairns J, Jr (ed.). CRC Press: Boca Raton, FL; 69–85.

Brenner FJ. 1985. Land reclamation after strip coal mining in the United States. *Mining Magazine* **September**: 211–217.

Carpenter SR. 1998. Ecosystem ecology. In *Ecology*, Dodson S, Allen T, Carpenter S, Ives A, Jeanne R, Kitchell J, Langston N, Turner M (eds). Oxford University Press: Oxford; 123–162.

Ehrenfeld JG. 2000. Defining the limits of restoration: the need of realistic goals. *Restoration Ecology* **8**: 2–9.

Evans K. 2000. Methods for assessing mine site rehabilitation design for erosion impact. *Australian Journal of Soil Research* **38**: 231–247.

Evans K, Loch RJ. 1996. Using the RUSLE to identify factors controlling erosion rates of mine soils. *Land Degradation & Development* **7**: 267–277.

Fifield JS. 1994. Evaluating the Effectiveness of Erosion and Sediment Control Plans. Course notes. Technical Workshop for The International Land Reclamation and Mine Drainage Conference. Pittsburgh, April 24–29. International Erosion Control Association: Tucson, AZ.

Haigh MJ. 1979. Ground retreat and slope evolution on regraded surface-mine dumps, Waunafon, Gwent. *Earth Surface Processes* **4**: 183–189.

Haigh MJ. 1980. Slope retreat and gullying on revegetated surface-mine dumps, Waun Hoscyn, Gwent. *Earth Surface Processes* **5**: 77–79.

Haigh MJ. 1985. The experimental examination of hill-slope evolution and the reclamation of land disturbed by coal mining. In *Geography applied to practical problems*, Johnson JH (ed.). Geo Books: Norwich; 123–138.

Haigh MJ. 1992. Problems in the reclamation of coal-mine disturbed lands in Wales. *International Journal of Surface Mining and Reclamation* **6**: 31–37.

Hancock GR, Evans KG, Willgoose GR, Moliere DR, Saynor MJ, Loch RJ. 2000. Medium-term erosion simulation of an abandoned mine site using the SIBERIA landscape evolution model. *Australian Journal of Soil Research* **38**: 249–263.

Kapolka NM, Dollhopf DJ. 2001. Effect of slope gradient and plant growth on soil loss on reconstructed steep slopes. *International Journal of Surface Mining, Reclamation and Environment* **15**: 86–99.

Kelsey K. 2002. Use of the revised universal soil loss equation on an event-by-event basis. *International Erosion Control Association Proceedings* **33**: 61–69.

Khanbilvardi RM, Rogowski AS. 1986. Modelling soil erosion, transport and deposition. *Ecological Modelling* **33**: 255–268.

Loch RJ. 1997. Landform design—Better outcomes and reduced costs applying science to above-and below-ground issues. *Proceedings of the 22nd Annual Environmental Workshop.* Minerals Council of Australia: Adelaide; 550–563.
Loch RJ, Sell K. 1998. Cost savings and improved management of rehabilitated slopes: benefits form a rainfall simulator study at the North Parkes mine. In *Environmental Management, 2*, Sivakumar M, Chowdhury RN (eds). *Proceedings of the Second International Conference on Environmental Management*. Elsevier: Amsterdam; 1187–1194.
Margalef R. 1968. *Perspectives of the Ecological Theory.* University of Chicago: Chicago, IL.
Margalef R. 1970. Explotación y gestión en ecología. *Pirineos* **98**: 103–121.
Minas y Ferrocarril de Utrillas SA. 2001. Diseño de la morfología y red de drenaje en las restauraciones mineras. Informe de Difusión de Proyectos No. 74. Ocicarbón-Ciemat: Madrid.
Mutz M, Lebmann D, Ender R, Schlief J. 2002. Development of sustainable streams after opencast coal mining in Lusatia, Germany. *Proceedings of the International Conference on Water Resources and Environment Research*, Vol. 3. Eigenverlag des Forums für Abfallwirtschaft und Altlasten e.V., Technische Universität: Dresden; 125–129.
Nicolau JM. 2001. Using RUSLE 1.06 to design landforms derived from opencast coal mining reclamation. *Proceedings of the International Conference on Sanation and Remediation of Post-mining Landscapes*. CD-ROM format. Teplice: Czech Republic.
Nicolau JM. 2002. Runoff generation and routing on artificial slopes in a Mediterranean-continental environment: the Teruel coalfield, Spain. *Hydrological Processes* **16**: 631–647.
Nicolau JM, Asensio E. 2000. Rainfall erosion on opencast coal-mine lands: ecological perspective. In *Reclaimed Land: Erosion Control, Soils and Ecology*, Haigh MJ (ed.). A.A. Balkema: Rotterdam; 51–73.
Osterkamp WR, Joseph WL. 2000. Climatic and hydrologic factors associated with reclamation. In *Reclamation of Drastically Disturbed Lands*, Barnhisel R, Darmody R, Daniels W (eds). ASA Monograph No. 41. American Society of Agronomy: Madison, WI; 193–216.
Palmer J. 1992. Nutrient cycling: key to reclamation success. In *Evaluating Reclamation Success: The Ecological Consideration*, Chambers J, Wade J (eds). General Technical Report EN-164. US Department of Agriculture: Washington DC; 27–36.
Pimentel D, Harvey C. 1999. Ecological effects of erosion. In *Ecosystems of Disturbed Ground*, Walker LR (ed.). Ecosystems of the World 16. Elsevier: Amsterdam; 123–136.
Porta J, Poch R, Boixadera J. 1989. Land evaluation and erosion practices on mined soils in EN Spain. *Soil Technology Series* **1**: 189–206.
Puigdefábregas J. 1996. El papel de la vegetación en la conservación del suelo en ambientes semiáridos. In *Erosión y Recuperación de Tierras en Áreas Marginales,* Lasanta T, García-Ruiz JM (eds). Sociedad Española de Geomorfología: Zaragoza; 79–88.
Riley SJ. 1995. Geomorphic estimates of the stability of a uranium mill tailings containment cover: Nabarlek, Northern Territory, Australia. *Land Degradation & Rehabilitation* **6**: 1–16.
Sanchez CE, Wood MK. 1989. Infiltration rates and erosion associated with reclaimed coal mine spoils in West Central New Mexico. *Landscape and Urban Planning* **17**: 151–168.
Sawatski L, McKenna G, Keys MJ, Long D. 2000. Towards minimising the long-term liability of reclaimed mine sites. In *Reclaimed Land: Erosion Control, Soils and Ecology*, Haigh MJ (ed.). Balkema: Rotterdam; 21–36.
Siefert J, Mutz M. 2001. Processing of leaf litter in acid waters of the post-mining landscape in Lusatia, Germany. *Ecological Engineering* **17**: 297–306.
Stiller DM, Zimpfer GL, Bishop M. 1980. Application of geomorphic principles to surface mine reclamation in the semiarid West. *Journal of Soil and Water Conservation* **35**: 274–277.
Toy TJ, Black JP. 2000. Topographic reconstruction: the theory and practice. In *Reclamation of Drastically Disturbed Lands*, Barnhisel R, Darmody R, Daniels W (eds). ASA Monograph No. 41. American Society of Agronomy: Madison, WI; 41–76.
Toy TJ, Foster GR. 1998. *Guidelines for the Use of the Revised Universal Soil Loss Equation (RUSLE) Version 1.06 on Mined Lands, Construction Sites and Reclaimed Lands.* Office of Surface Mining, Denver, CO.
Toy TJ, Hadley RF. 1987. *Geomorphology of Disturbed Lands.* Academic Press: New York.
Toy TJ, Osterkamp WR. 1995. The applicability of RUSLE to geomorphic studies. *Journal of Soil and Water Conservation* **50**: 498–503.
Weltz MA, Kidwell MR, Fox HD. 1998. Influence of abiotic and biotic factors in measuring and modeling soil erosion on range-lands: state of knowledge. *Journal of Range Management* **51**: 482–495.
Willgoose G, Riley S. 1994. Long-term erosional stability of mine spoils. In *The AusIMM Annual Conference*. Darwin, Australia, 5–9 August 1994. 423–427.
Willgoose G, 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 Surface Processes and Landforms* **23**: 237–259.
Young J. 1992. Population-level processes: seed and seedbed ecology. In *Evaluating Reclamation Success: The Ecological Consideration*, Chambers J, Wade J (eds). *General Technical Report* NE-164. US Department of Agriculture: Washington, DC; 37–46.

