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Restoring earth surface processes through landform design. A 13-year monitoring of a geomorphic reclamation model for quarries on slopes

J.F. Martín-Duque,[1] * M.A. Sanz,[1] J.M. Bodoque,[2] A. Lucía[1] and C. Martín-Moreno[1]
[1] Department of Geodynamics, Faculty of Geology, Complutense University of Madrid, Spain
[2] Department of Mining and Geological Engineering, Castilla La Mancha University, Toledo, Spain

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*Correspondence to: José F. Martín Duque, Deparment of Geodynamics, Faculty of Geology, Complutense University, C/José Antonio Novais 8, 28040 Madrid, Spain. E-mail: josefco@geo.ucm.es

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ABSTRACT: The application of geomorphic principles to land reclamation after surface mining has been reported in the literature since the mid-1990s, mostly from Australia, Canada and the USA. This paper discusses the reclamation problems of contour mining and quarries on slopes, where steep gradients are prone to both mass movement and water erosion. To address these problems simultaneously, a geomorphic model for reclaiming surface mined slopes is described. Called the 'highwall–trench–concave slope' model, it was first applied in the 1995 reclamation of a quarry on a slope (La Revilla) in Central Spain.

The geomorphic model does not reproduce the original topography, but has two very different sectors and objectives: (i) the highwall–trench sector allows the former quarry face to evolve naturally by erosion, accommodating fallen debris by means of a trench constructed at the toe of the highwall; (ii) the concave-slope base sector, mimicking the landforms of the surrounding undisturbed landscape, promotes soil formation and the establishment of self-sustaining, functional ecosystems in the area protected from sedimentation by the trench. The model improves upon simple topographic reconstruction, because it rebuilds the surficial geology architecture and facilitates re-establishment of equilibrium slopes through the management and control of geomorphic processes.

Thirteen years of monitoring of the geomorphic and edaphic evolution of La Revilla reclaimed quarry confirms that the area is functioning as intended: the highwall is backwasting and material is accumulating at the trench, permitting the recovery of soils and vegetation on the concave slope. However, the trench is filling faster than planned, which may lead to run-off and sedimentation on the concave slope once the trench is full. The lesson learned for other scenarios is that the model works well in a two-dimensional scheme, but requires a three-dimensional drainage management, breaking the reclaimed area into several watersheds with stream channels. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: geomorphic reclamation; landform design; quarry reclamation; hillslope evolution of reclaimed mines; Segovia province (Central Spain)

Introduction

This paper discusses a geomorphic model for the reclamation of an abandoned silica sand quarry on a slope of Central Spain (La Revilla), and documents its 13-year geomorphic and edaphic maturation. Reclamation was planned and executed using geomorphic principles, and it involved local landform-based topographic reconstruction, replacement of original surficial deposits and management of the long-term geomorphic dynamics. The logic behind this study requires an understanding of the role of geomorphic processes in mining reclamation with attention to the specific rehabilitation problems of quarries on slopes, so this background is presented before discussing the study in detail.

Mining moves earth and shapes new landscapes

Cumulative effects of human-induced earth movements have a profound effect on global change (Osterkamp and Morton, 1996): 'humans are arguably the most important geomorphic agent currently shaping the surface of Earth' (Hooke, 1994, p. 217; Hooke, 1999). In particular, surface mining is most efficient at moving earth (Hooke, 1994).

Surface mining imposes severe ecological effects on the land because alteration affects vegetation, soils, bedrock and landforms. Surface hydrology and groundwater levels and flow paths are also changed (Osterkamp and Joseph, 2000; Nicolau and Asensio, 2000).

The science of geomorphology, which deals with the study of earth's landforms and the surface processes by which they are shaped (Godfrey and Cleaves, 1991), provides a useful framework both for an understanding of the environmental effects of surface mining, including changes in erosion–sedimentation processes and soil properties (Wilkinson and McElroy, 2007), and for designing the most appropriate strategies for reclamation (Toy and Hadley, 1987).

Surface mining reclamation allows the design and complete reconstruction of new landforms. This is different, for instance, from the rehabilitation of roadcuts and earthfills in highway construction, or housing developments, where there is a limited possibility for geomorphic design (Nicolau, 2003). Landform reconstruction is the major phase of the mining reclamation process; and earth movement is the most expensive part of reclamation (Brenner, 1985; Zipper *et al.*, 1989; Environment Australia, 1998). Finding the appropriate landform design in mining reclamation can be simultaneously effective in ecological and economic terms (Sawatsky *et al.*, 1998).

Geomorphic reclamation in surface mining

The landforms that traditionally result from reclaimed mining cuts and spoil banks nearly always have a geometric topography – constant-gradient slopes with benches (graded banks, terraced appearance). They are usually combined with elements to redirect and slow runoff, such as rip-rap, erosion control blankets, rock-filled gabions, drainpipes, concrete linings or blocks (Nicolau 2002, 2003; Bugosh, 2006a).

The reasons argued for these designs are: (i) their geotechnical stability, which helps prevent mass movement (landslides, failures of tailings dams, etc.); (ii) the runoff management from the slopes; and (iii) their ease of construction using existing machinery. The geometric topography of mined landscapes is often regulated by specific technical instructions of mining safety, as is the case in Spain.

However, 'very few linear slopes with benches are observed in nature' (Hancock *et al.*, 2003, p. 1097). Reclamation landforms built using conventional methods 'depart considerably from the stable natural landforms surrounding them, both in performance and appearance' (Bugosh, 2006a, p. 156). Nor are these reconstructions always successful: without on-going maintenance, many graded banks fail under water erosion over the long term (Loch, 1997). Further, the most convenient geometry for controlling mass movement is not usually the optimum geometry for minimizing erosion (McPhail and Rusbridge, 2006). According to Sawatsky *et al.* (2000), the traditional approach of uniform slopes and terracing in mining reclamation results in an immature topography not present in nature. The slopes are poised to evolve by accelerated erosion and the terraces can increase erosion during extreme events when their storage capacity is exceeded. Therefore, more than appearance, the main shortcoming of conventional designs in mining reclamation is that they give 'little consideration for proper hydrologic function for balanced conveyance of water and sediment from the land surface' (Bugosh, 2004, p. 241). This often results in high maintenance and liability costs. Anticipation of these costs in a mine permit review can halt a proposed mine opening or expansion, and in extreme cases actual failures can halt active mining (Bugosh, 2004, 2009).

Many researchers have reported the hydrologic instability of rectilinear and terraced slopes on mine spoil dumps. Haigh pioneered the study of water erosion processes and slope evolution of surface mine dumps, showing the accelerated erosion of rectilinear slope segments (Haigh, 1979), leading to gully development (Haigh, 1980). Goodman and Haigh (1981), studying slope evolution on abandoned spoil banks of different ages in Eastern Oklahoma, found a marked tendency for the reduction of slope crests, the burial of the toe slopes, and the extension of the upper convexity and lower concavity at the expense of the rectilinear main slope of the original mine dump. Haigh (1985) summarized this general tendency of slope evolution for initially rectilinear slope profiles of mine spoil mounds: they evolve towards a much more stable sigmoid shape.

In the long term, many of the geometric slopes are prone to severe erosion, and once this failure has occurred, they channel water in concentrated flow paths, leading to severe gullying (Hancock *et al.*, 2003; Sanz *et al.*, 2008). Sawatsky and Tuttle (1996) suggested that gully erosion can be used as an indicator of the performance and sustainability of mining reclamation. This is because erosion on mined landforms seeks to re-establish the dynamic equilibrium between landforms and processes. Proper landform design in mining reclamation can accomplish part of this work, leaving the 'fine-tuning' to natural processes (Schumm and Rea, 1995; Toy and Black, 2000; Toy and Chuse, 2005). Therefore, the design of reclaimed landforms into the shape that geomorphic processes would tend to erode them under existing environmental conditions should be the aim of any surface mining reclamation (Bugosh, 2004, 2007).

As various countries started to enforce the protection of aquatic ecosystems located downstream from disturbed (mined) areas (e.g. the US Clean Water Act of 1972), investigators, practitioners and regulators began to show much more interest in the off-site environmental impacts of runoff and erosion from mined lands and to place more emphasis on long-term stability. Unstable landforms prevent the development of soils and vegetation communities, and erosion control is difficult and uneconomical (Riley, 1995; Toy and Black, 2000; Kapolka and Dollhopf, 2001); by contrast, geomorphic-based sustainable landscapes are expected to generate efficient engineering solutions that generally decrease ecological impacts (Bender *et al.*, 2000). Compatibility between environmental protection and mine profitability can be achieved through integrated minewater management (Sawatsky *et al.*, 1998). Bugosh (2009) documented that the quality of runoff water from mined lands reclaimed using fluvial geomorphic criteria can be equal to or better than that of contiguous natural lands. In arid and semiarid areas, however, erosion control and runoff water quality are not the only issues; alternative approaches that mimic the geomorphic function of the natural landscape can 'harvest' water, providing a key factor in the restoration of ecosystems in water-scarce environments (Bugosh, 2004).

Long-term stability against water erosion is also very important in sensitive environments, such as the aquatic ecosystems of Upper Tagus region of Spain (Sanz *et al.*, 2008) or when dealing with tailings containing long-lived radionuclides, where structures need to be stable for at least 1000 years (Willgoose and Riley, 1998).

In this framework, where geometric designs dominate, many authors have argued in favour of geomorphic approaches: 'nature can provide analogues for post-mining landscapes in terms of landscape stability and also in terms of the rehabilitated structure blending in with the surrounding undisturbed landscape' (Hancock *et al.*, 2003, p. 1097); designing slopes and landforms based on natural ones can achieve the dual goal of being more visually attractive and being more functional and cost effective (Schor and Gray, 2007); landform design in mining reclamation should make the final landform hydrologically, geomorphologically and visually compatible

Table I. Differences between the traditional and geomorphic approaches to surface mining reclamation

	Traditional (geometric) approach	Geomorphic approach
Geomorphic stability	Short-term stability (mainly for mass movements), but failure under water erosion over the long term	Long-term stability (mainly against water erosion). Dynamic equilibrium between landform and processes
Visual character	Artificial appearance (*e.g.*, terraced), usually located within natural landscapes	Natural appearance, blending in with the surrounding landscape
Ecological	Results in a simpler ecosystem	Designed to support functional and self-sustained ecosystems that replicate the natural ones
Resilience	Not resilient	Resilient
Maintenance	Requires on-going maintenance	It reduces or eliminates any maintenance
Costs	More expensive because artificial elements and maintenance are required	Less costly than conventional reclamations, in both the short and long term
Sequential use	Limited options for sequential use	Options for sequential use

with the surrounding area and remain stable for the long term (Hancock *et al.*, 2003); the design of mature landforms 'serves to improve the aesthetic appearance, provide a wider range of habitats for wildlife and avoid the large surface-flow rates typical of long, straight slopes' (Sawatsky *et al.*, 2000, p. 28). Sustainable reclaimed mined landscapes over the long term can be achieved through attention to geomorphic parameters (Table I) (Riley, 1995; Keys *et al.*, 1995).

The use of geomorphic principles in surface mining reclamation is well established in Canada, Australia and the United States. In Canada, Sawatsky and Beckstead (1996) and Sawatsky *et al.* (1996, 1998) call for the application of geomorphic principles in the design of mined land reclamation for integrated minewater management. Contributions from Australia integrate geomorphological, hydrological and ecological principles in the reclamation of areas affected by surface mining, often using SIBERIA landscape evolution software (Riley, 1995; Evans and Loch, 1996; Loch, 1997; Environment Australia, 1998; Willgoose and Riley, 1998; Evans and Willgoose, 2000; Evans *et al.*, 2000; Hancock *et al.*, 2003). In the USA, the contributions of Toy and collaborators are benchmarks in this field (Toy and Hadley, 1987; Toy and Foster, 1998; Toy and Black, 2000; Toy and Griffith, 2001; Toy and Chuse, 2005). Also outstanding in the USA is a specific landform design software (Natural Regrade with GeoFluv^{TM}), driven by geomorphic principles (Carlson Software and Bugosh, 2005). This method tackles most of the geomorphic arguments because it essentially reproduces the natural landform's evolution to the mature stage, resulting in stable slopes and channels, in balance with the local environmental conditions (Bugosh, 2004, 2007). The US Office of Surface Mining (OSM) awarded 'National' and 'Best of the Best' awards to reclamation projects using this approach (Bugosh and Eckels, 2006).

The possibilities of applying geomorphic approaches to surface mining reclamation depend on: (i) the nature of the extracted mineral; (ii) the exploitation method; (iii) the final shape of the mined landscape; and (iv) the lithologies of the new landforms (highwalls, benches, terraces, waste dumps, etc.). Table II characterizes the reclamation geomorphic framework of the most common types of surface mining.

The specific problems of contour mining and slope quarrying

Because of their steep slopes, contour mining and quarrying on slopes create specific reclamation difficulties favouring slope instability and water erosion, allowing sediments to reach stream channels below the mines. Eventually, more distant streams and rivers can be affected.

Contour mining is commonly used to extract coal, producing large volumes of mine spoil. This type of mining was dramatically altered in 1977 in the USA by enactment of the Surface Mining Control and Reclamation Act (SMCRA), which required that all mining spoil had to be stabilized and returned to the 'approximate original contour (AOC)' (Brenner, 1985). It meant that the extensive highwall cuts had to be covered and returned to contour. This act has had an important impact on reclamation in other countries.

The AOC requirement led to some controversial practices. Several authors (Brenner, 1985; Bell *et al.*, 1989; Zipper *et al.*, 1989;) felt that the near-universal use of the AOC requirement in the steeply sloping topography of the Appalachians was not appropriate, and that it led to common slope instability, excessive mining costs, increased erosion and loss of post-mining land-use value. The main reason for these failures is that this type of reclamation cannot replicate the original geologic structure and soil properties. Haigh (1992) provides a similar example of mining reclamation failure in Wales.

As the above examples illustrate, the emphasis in reclamation is too often on the restoration of topography, without considering the structure and nature of the materials beneath. Commonly, a former topography based on bedrock is reconstructed with spoils, changing slope stability conditions dramatically. Therefore, a truly geomorphic approach to surface mining reclamation should always consider that the surficial geology may have a major effect on surficial and subsurficial hydrology, and therefore on the long-term stability of the reclaimed landforms. This consideration may lead to landform designs different from the original contour. This circumstance is not automatically adverse: 'it cannot be assumed that pre-disturbance equilibrium landforms are necessarily post-reclamation equilibrium landforms' (Toy and Black, 2000, p. 45). Bugosh (2006b) coined the term 'asteroid effect' to describe the effect of a surface mine on earth materials; the loose backfill compares with the pre-mine consolidated rock as the earth material remaining after an asteroid impact compares with the pre-impact rock. Consequently, the unconsolidated backfill usually demands a very different landform to achieve stability against erosion. For instance, whereas the pre-mine consolidated rocks can have different drainage patterns, a dendritic drainage pattern can better suit the reclamation, because it is typical of unconsolidated materials (Bugosh, 2004). Summing up, the SMCRA shows an example in which the AOC requirement resulted in a very uniform mining reclamation. Too restrictive regulations can discourage the development of innovative techniques, showing that 'no single reclamation strategy is applicable to all environments' (Brenner, 1985, p. 217).

The quarries on slopes differ topographically depending on whether or not the material exploited is consolidated. A

Table II. Common surface mining methods and possible geomorphic approaches to their reclamation

Mining method		Most common mineral resource and topography	Most common resultant landform with no reclamation	Traditional and most common landform with reclamation	Main geomorphic reclamation constraints	Geomorphic approach to reclamation (theoretical or actual); literature references
Open pit		Low grade high volume. Mainly metals (also coals)	Benched circular pit, with outside waste dumps	Terraced waste dumps on valleys or heads of hollows	Large pits; visual impact; runoff and erosion of dumps	Dumps designed to replicate local landforms
Strip / area		Strata bound. Mainly coals in flat to moderately-rolling terrain, with thin surficial mineral	Benched rectangular shallow large pit with outside waste dumps	Transfer mining – backfilling in terraced platforms (linear platform-bank model), or smooth (for farming or forest use). Large lakes from deep pits	Large-scale earth movements	Hydrological basins in final pit (Willgoose and Riley, 1998; Sawatsky *et al.*, 1998; Nicolau, 2003). The Fluvial Geomorphic Approach (Bugosh, 2004, 2006a, 2009). Recovery of pre-disturbance contours (Sánchez and Wood, 1989)
Terracing		Mainly coals in flat terrain, with deep or thick deposits	Benched rectangular deep large pit with outside waste dumps			
Mountaintop removal		Coals that underlie the top of mountain ridges	Benched pit with outside waste dumps	Terraced waste dumps on slopes, valleys and head-of-hollow fills	Off-site effects of runoff and erosion from waste dumps	The USA as example: after the SMCRA of 1977, replication of the ‘approximate original contour’. Backfilling of original slopes (Bell *et al.*, 1989; Zipper *et al.*, 1989)
Contour		Mainly coals mined in hillsides and steep terrain	Highwall–bench-outslope topography from ‘shoot-and-shove’ mining: the blasted or dug overburden is either shoved downhill or chaotically left on the bench	Highwall benching and terraced waste dumps on slopes, valleys and head-of-hollow fills. Visual screens	On-site and off-site effects of runoff erosion; visual impact; highwall instability; spoils often scarce	
Quarries	*Slope*	Mainly industrial and construction rocks and minerals				Highwall–trench- concave slope (Martín Duque *et al.*, 1998)
	Pit	Mainly ornamental rocks (e.g. granites)	Benched rectangular pit and chaotically arranged rock blocks and spoils	Rehabilitation of terraced topography on bedrock for vegetation establishment	Scarcity of waste dumps to restore soils and vegetation cover	Re-shaping of terraced topography following geomorphic principles. Hydrological basins
Gravel pits		Aggregates, gravel, and sand in floodplains and terraces	Rectangular single benched pit. Often intersects groundwater table	Filling of hollows and topsoiling (farming use). Artificial lakes (natural use)	Scarcity of waste dumps for landform design. Pit often below water table	Design of ecologically functional wetlands following principles of fluvial processes

SMCRA = United States Surface Mining Control and Reclamation Act (1977) typical quarry on a slope, as the one in Central Spain analysed in this paper, typically consists of: (i) a main highwall, vertical or terraced; (ii) a main slope shelf or bench (mine platform); and (iii) the waste dumps, usually scarce when most of the rock or mineral is removed. In general, the final cut is large in comparison with the spoils. For this situation, the reclamation problems (as shown in Table II) are: (i) the highwall stability; (ii) the reclamation of the mine platform and any hillside construction within it; (iii) the management of the waste dumps; (iv) the visual impact of the highwall cut; and (v) the potential on-site and off-site effects of runoff and erosion.

This paper describes a 13-year monitoring of a slope geomorphic reclamation model that has dealt with most of these referred reclamation problems at one time – without returning the original contour, without the highwall elimination, and with the reconstruction of only a sector of the slope. For that, the landform design was inspired by the knowledge of the dynamics of local geomorphic processes.

Case and study area: the reclaimed quarry of La Revilla (Segovia, Spain)

La Revilla quarry yielded silica sand sediments of Central Spain (Segovia province), of Upper Cretaceous age. In this region, these silica sands are on the slopes of limestone and dolostone-capped mesas and cuestas, but they crop out only in slope gullies because the mesas' silica sand hillslopes are always covered with a carbonate colluvium. On these slopes, rendzic leptosols develop on the consolidated limestones and dolostones of the mesas' and cuestas' rims, and colluvic regosols develop on the carbonatic colluvium that drapes the silica sand (IUSS Working Group WRB, 2007).

The climate is characteristic of the Mediterranean Basin, with a moderate average annual precipitation (679·1 mm) and temperature (11·4°C). Due to this area's great distance from the sea, its high altitude (1050 m above sea level, m.a.s.l.) and its proximity to the mountain Central System of the Iberian Peninsula, the winters are long and cold. Temperatures below –10°C are not uncommon, and snow days average 13 annually. The summers are short, very dry, and hot, with maximum daily temperatures frequently close to 40°C.

These climatic conditions and intense human use of the land for more than 1000 years have resulted in characteristic open woodlands of holm oak *(Quercus ilex*, subsp. *rotundifolia)*, white savin juniper *(Juniperus thurifera)*, and juniper shrubs *(Juniperus communis* subsp. *hemisphaerica)*.

At La Revilla quarry, the silica sand was extracted during the 1970s, a period in which the Spanish legislative system lacked mining reclamation requirements; the first Spanish mining reclamation act was enacted in 1982. The sand at La Revilla was quarried by directly excavating the slopes. The removed surficial deposits and spoils were either left at the mine's bench or pushed downhill, burying the original soils downslope. The result was a highwall–bench–outslope topography, which left the silica sand and clay spoils exposed, with almost no soil properties (Figure 1). From the area's abandonment to its reclamation, a progressive degradation took place. Within the abandoned mine (on-site), intense erosion and sedimentation occurred, whereas downslope from the mine (off-site), severe soil degradation and river silting occurred.

At the beginning of 1994, an opportunity to reclaim this mine was supported through a programme of subsidization by the regional government (Castilla y León), which targeted abandoned mines exploited before 1982. The reclamation project was approved in 1994, and implemented in January and February of 1995.

Figure 1. The abandoned silica sand quarried slope of La Revilla, before its geomorphic reclamation: appearance of the exploited quarry at the slope of a limestone-capped small mesa, and highwall–bench–outslope topography, with a chaotic arrangement of scarce silica sand and clay spoils.

For the geomorphic reclamation model design, the chaotic arrangement of mine dumps upon the bench of the abandoned quarry required a new geomorphic reconstruction and a major classification and movement of earth. The aim of this geomorphic reclamation was to re-establish a process-landform (Toy and Hadley, 1987) – in other words, to implement the desired processes by designing and building the appropriate landforms. For that, a highwall–trench–concave slope topographic model with two very different sectors and objectives was proposed (Figures 2 and 3):

(1) *The highwall–trench sector*. The existing quarry highwall would be allowed to degrade in a natural manner, mainly by mass movement. This approach would accommodate the fallen debris in a trench constructed at the toe of the highwall, so that: (i) they would not overrun the reconstructed concave hillslope toe, where geomorphic stability would permit soil formation; (ii) the accumulation of the fallen debris would imitate, in the long term, the topography and structure of the slopes of the area. In short, at the highwall–trench sector, the geomorphic activity and instability would be allowed to interact.

(2) *The concave slope sector*. On the former quarry floor, a concave hillslope base was designed to fit the profile of the surrounding undisturbed landscape. The objectives were: (i) long-term geomorphic stability (lack of soil erosion), (ii) soil formation, (iii) the establishment of self-sustaining and functional ecosystems. A concave slope was considered the most appropriate, because it replicated the runout gradients of local natural slopes surrounding hillslope bases. It was also estimated to be the most geomorphologically stable, since as the catchment area increases, slope decreases, reducing the velocity of discharge and its erosive potential (Hancock *et al.*, 2003). Actually, this is what natural slope analogues show us: the toe of a natural (erosion-resistant) slope has a lower gradient than the upslope, resulting in a reduced erosion potential.

Excavating a trench in order to disconnect the concave slope from the highwall was a key design feature for the reclamation (see Figure 3), because the decoupling of the two slope segments limited the oversteeping of the concave hillslope toe by slope deposits from the highwall. The geometric model for the optimization of waste dumps in the topographical reconstruction is described in detail in Martín-Duque *et al.* (1998).

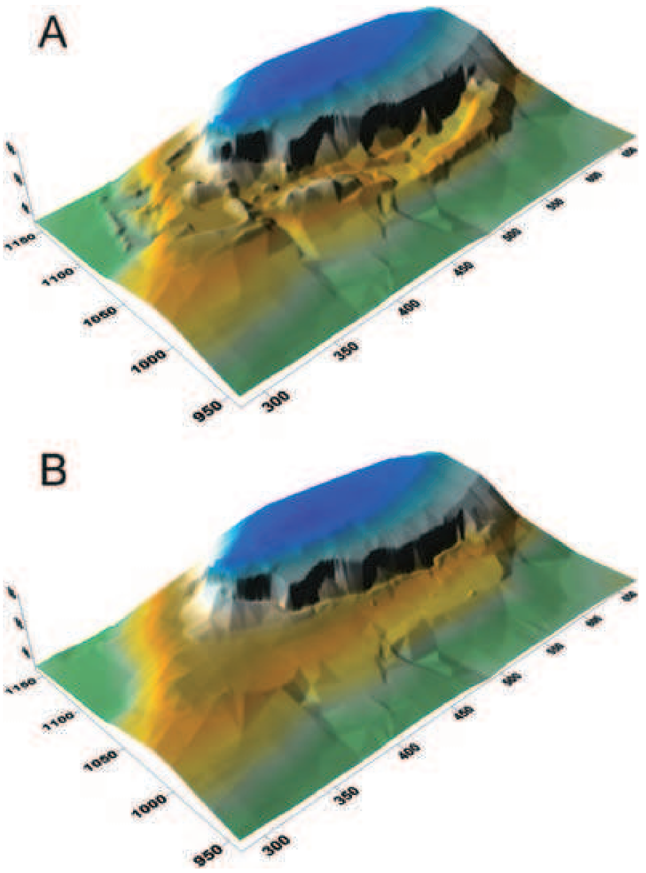

Figure 2. Topographic comparison of the quarried slope before (A) and after (B) its geomorphic reclamation. Relative coordinates are in m.

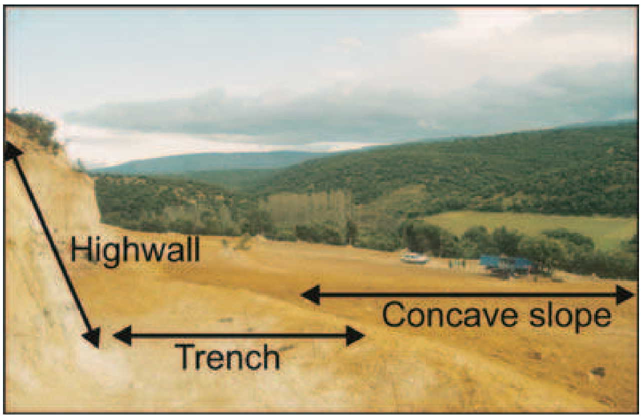

Figure 3. Detail of the highwall–trench–concave slope geomorphic model, represented on a photo taken in February 1995, immediately after reclamation was completed.

The landform design included not only a topographical reconstruction, but also an appropriate arrangement of the substratum and the surficial deposits. The sandy spoil heaps, which had no edaphic capacities, were planned to be placed as substrata of the concave slope base and covered with the carbonate colluvium. This assemblage of surficial materials replicated the natural proto-soil of local slopes.

This carbonate colluvium previously covered the quarried hillslope. It was a surficial deposit derived from the break up and decomposition of the limestone and dolostone rocks that capped and rimmed the exploited silica sands. Our strategy was that carbonatic colluvium was an optimum starting point for soil formation at the concave slope, given that: (i) it formed the original substrata of the local hillslope soils on which the mining activity took place; (ii) its loamy texture made it ideal for edaphic development, allowing a balance between an optimum drainage and the accumulation of water and nutrients, making possible the formation of soil aggregates; and (iii) it had a high calcium content (average of 217·6 mg per 100 g), which helps to create the slightly basic pH optimum for nutrient production for plants and improves the soil development and structure.

The execution of this geomorphically-guided reclamation took place between January and February of 1995. For an understanding of the 13-year spontaneous evolution of the reclaimed area, it is required to know that the reconstructed concave slope: (i) was sown with a 330 kg ha^{-1} mixture of grass and leguminous seed; (ii) was fertilized the first year with a complex fertilizer in a proportion of 12/36/12 (nitrogen/phosphorus/potassium) at 600 kg ha^{-1}, to ease the problem of the initial deficiency of nutrients in the carbonatic colluvium. Following the reclamation work, the area has been used solely for livestock (sheep) grazing with no further maintenance. Details beyond those summarized here, and the precise location of the reclaimed quarry, are described in Martín-Duque *et al.* (1998).

Methodology

To assess whether the reclaimed surface followed the hypothesized evolution, the area was monitored from the spring of 1995 to the spring of 2008 (Table III). This observation period is within an appropriate order of magnitude for documenting the beginning of the geomorphic evolution of the highwall (when most of it is cut in poorly consolidated sands) and of the edaphic evolution of the reconstructed concave slope.

Topographical survey

A topographic survey of the reclaimed area was made with a total station on May 1995. From it, a digital elevation model (DEM) of the former highwall–trench sector was extracted. Twelve years later, in June 2007, a high-definition topographic survey of the same area (the highwall–trench sector) was carried out using newly available terrestrial laser scanner (TLS) technology. Although comparison between both topographical surveys is inherently difficult, a contrast of different topographical profiles (2D) and of the 3D surfaces of the highwall could be made. The 2D topographical profile comparisons offered satisfactory results, but the 3D comparisons were inadequate, due to the precision and different means of obtaining the data in 1995 and in 2007. Therefore, a method for assessing the 3D topographical evolution of the highwall–trench sector was developed. Areas of the highwall that had not suffered either erosion or sedimentation during the monitored period were identified in the 2007 laser scanner point cloud. Those areas remained as small spots, almost vertical sand and limestone cliffs, and were recognized based on the ground photo survey. With the point cloud of those stable areas of the highwall, a DEM of the former highwall was interpreted. It was done by generating 'surfaces of tendency' for those spots that later suffered erosion or sedimentation. For this analysis, the interpolation methods were based on the analysis of the semivariograms and on kriging interpolators. Finally, a 3D comparison was made between the 2007 real topography – obtained using the TLS – and the 1995 topography – obtained from interpretation of the 2007 surfaces that had not suffered erosion or sedimentation.

Table III. Monitoring procedures applied to the reclaimed quarried slope of La Revilla

Year	Highwall–Trench		Concave slope		Entire reclaimed area
(Spring)	Topographical survey	Ground photo survey	Bare soil cover survey	Soil analysis	Oblique aerial photo survey
1995	X	X	X	X	
1996		X			X
1997		X	X		
1998		X		X	
1999		X			X
2000		X			
2001		X	X		
2002		X	X	X	X
2003		X	X		
2004		X	X		
2005		X	X	X	X
2006		X	X		
2007	X	X	X		
2008		X	X	X	X

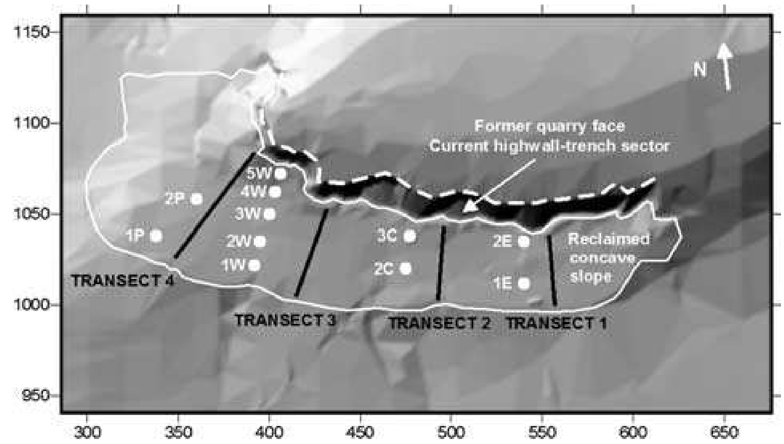

Figure 4. Location of the four transects (in black) for the soil cover survey of the reclaimed concave slope. In each transect, a total of seven fix plots measuring 1 × 1 m have been surveyed since 2001 for edaphic cover; number 1 was downslope through number 7 upslope. The figure also shows the location of the edaphic sample points (in white) described in the text. Sampling points 5W, 1P and 2P were not analysed in 1998, but they were analysed in 2002, 2005 and 2008. Relative coordinates are in m.

Ground photo survey

A second procedure to monitor the geomorphic evolution of the former quarry face was a periodic photographic survey of the highwall–trench sector. Ground photos were taken annually, during the month of June, from reference points marked on the ground with wooden pegs.

Soil cover survey

The absence of geomorphic activity in the reconstructed and seeded concave slope base, and the tendency towards soil and vegetation development, were monitored by: (i) quantifying the percentage of bare soil in specific and fixed plots; and (ii) assessing the existence of microforms which indicate active hydric erosion processes (sheet erosion, rill erosion), as well as sedimentation (sand flats, sand sheets).

A first bare soil assessment was done in May of 1995 for the entire reclaimed concave slope. Then, a quantitative general assessment of seven plots was carried out in 1997. Finally, a much more detailed and systematic survey has been done annually since May 2001. For the latter, four 1 m wide transects were drawn out from the highwall to the beginning of the reclaimed area. In each transect, a total of seven inventories measuring 1 × 1 m were carried out, corresponding to a total of 28 plots measuring 1 × 1 m (Figure 4).

Soil analysis

To obtain information about the existence of edaphogenic processes and about the consequent absence of erosive geomorphic activity (according to the geomorphic reclamation approach), a series of spatial and temporal soil analyses were conducted at the reconstructed concave slope. This was done by looking for the variation in soil quality (Larson and Pierce, 1994; Doran *et al.*, 1996; Seybold *et al.*, 1997; Brejda *et al.*, 2000; Aparicio and Costa, 2007). The monitoring was based on the chemical analysis of the soil indicators that change most quickly on young substrates: (i) organic matter (o.m.); (ii) the ratio of carbon to nitrogen (C/N); (iii) exchangeable base cations; and (iv) assimilable phosphorus (P_20_5).

The soil quality characteristics of the surficial materials used as the 'starting point' edaphic substratum (carbonatic colluvium) and of the soils surrounding the quarry were determined in 1995. The variation and evolution undergone by the edaphic substratum of the concave slope have been monitored through analyses carried out in 1998, 2002, 2005 and 2008. To determine the existence or absence of variation in edaphic properties with slope (at this reconstructed concave sector), the sample points were located by following three longitudinal transects in the direction of the maximum slope (see Figure 4). The sampling plots were marked with wooden pegs. Since the initial variation in edaphic properties takes place in a very superficial level, the samples in the field were taken within the first 5 cm of soil, after removing the vegetation and biomass accumulation from the surface.

Data analyses were accomplished following three approaches. First by a simple comparison between mean values of edaphic indicators for different spatial and temporal situations. Second, to determine the extent to which the subsurficial hydrological dynamics are being recovered in the concave slope sector, slope gradients were sought by seeking variations of the soil elements or compounds susceptible to movement by (sub)surface runoff. Thus, a comparison of the referred soil indicators was performed in the upper and lower sectors of the reclaimed concave slope. Third, with the aim of measuring variations in soil properties with time, a multiple-sample comparison analysis was carried out based on ANOVA and by applying Fisher's test. Once ANOVA was accomplished, a multiple-range test was done to identify which means (obtained from sampling accomplished in 1998, 2002, 2005 and 2008) were significantly different from others.

Oblique aerial photo survey

For documentation of the visual evolution of the entire reclaimed area, a comparison of oblique aerial photographs was made. These photos were taken by a specialized company (Paisajes Españoles S.A.) in 1996, 1999, 2002, 2005 and 2008. The photos were taken with an Asahi Pentax camera with a 75 mm lens, with a 6 × 7 cm negative.

Results

Topographical survey

The topographic surveys helped turn the physical landscape of the reclaimed La Revilla quarried slope area into constructs from which observations and measurements could be made.

Figure 5A shows the 1995 total station topography of the highwall–trench sector of the reclaimed quarry. Figure 5B shows the 2007 detailed topography of the same area with TLS. Figure 6 shows an example of the topographical comparison of a profile of the highwall–trench sector. The difference in the appearance of Figure 5A and 5B, and of the stroke of the profile lines (Figure 6), is due to the different precision of the topographical instruments.

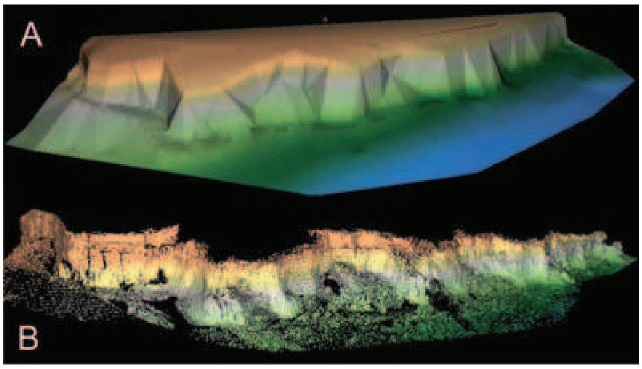

Figure 5. (A) Upper, 1995 total station topography of the highwall–trench sector. (B) Lower, detailed topography of the same area in 2007 (with laser scanner technology).

Finally, Figure 7 represents the 2007 DEM of the highwall, showing the location of the main erosive and depositional features: sand fall scars (at the highwall) and sand slopes and cones (at the trench). Also shown are two examples of the 1995 and 2007 3D comparisons.

Ground photo survey

Ground photos taken yearly documented the changes on the earth surface after the geomorphic reclamation. Earth falls, rock falls, and rill erosion occurred in the upper part of the highwall and fallen material accumulated in the trench, forming debris and sandy slopes and sand cone deposits. These features can be seen in the contrast of the four selected photo control points of the highwall–trench sector at different times (Figure 8).

The majority of the mass movements were recorded after the autumn-to-spring cycles of 1997–1998 and 2002–2003, when a series of voluminous falls occurred, forming a general sand talus at the foot of the highwall.

Soil cover survey

Vegetation rapidly appeared on the concave slope: by May of 1995, 30% of the reclaimed slope was already covered with vegetation. In 1997, there was more vegetation cover than bare soil and the pattern continued until, in 2008, less than 5% bare soil remained. Figure 9, which plots mean values, is based on data shown in Table IV.

Soil analysis

Table V and Figure 10 compare mean values of the analysed soil indicators for different situations. Because there are no historical data for establishing the 'reference' ecosystems or 'baseline conditions', the first row is filled with question marks. The second row shows mean values for soils in slopes adjacent to the mining exploitation, based on measurements in 1995, just before the reclamation began. These soils are characterized by being deeply modified by human activity – mainly deforestation, crops and overgrazing. Values of the starting point soils in 1995, at the reclaimed concave slope area, appear in the third row. Finally, the mean values for 1998, 2002, 2005 and 2008 are given in the balance of the Table V. From Figure 10 it can be emphasized the progressive and evident increase in mean content of organic matter of the soils of the reclaimed concave slope, from 0·31% in 1995 to 1·99% in 2008. The ratio of carbon to nitrogen (C/N) points to a slow mineralization process at the reclaimed area. And the results for exchangeable base cations and assimilable phosphorus are more conclusive in the following analysis.

Assimilable phosphorus shows a difference between the upper and lower sectors of the concave reclaimed slope, with a positive variation in the downslope direction (Table VI and Figure 11). This seems to be related to a downslope migration of P_2O_5 with time, which might explain the high dispersion of the standard deviation for P_2O_5 in Table V and Figure 10. Organic matter shows a similar pattern (Table VII), although the percentage of organic matter in 2002 was higher in the upper sector of the slope.

Finally, the results obtained from the ANOVA analysis, as well as those from the multiple range tests, lead to the conclusion that mean values for organic matter show increasing statistically significant differences between homogenous groups established from sampling carried out between 1998, 2002 and 2005. However, between 2005 and 2008, an increase in the percentage of organic matter is suggested, but it was not statistically significant. In contrast, mean values for exchangeable base cations defined decreasing – statistically significant – differences for all established homogenous groups (Tables VIII and IX).

Oblique aerial photo survey

Figure 12 documents the visual evolution of the reclaimed quarry. The former quarry face has evolved in a pattern equivalent to gullies and scarps of the area. The concave slope has been colonized by the native vegetation of the surroundings, experiencing a self-sustained vegetation succession with the recovery of the local ecosystems. Slope evolution at the highwall–trench sector can be also seen in these photos. The result is a visual integration of the whole reclaimed area into its environment, blending it with the surrounding landscape in landforms, texture, and colour.

Figure 6. Highwall's profiles comparison: 1995 (dark-rectilinear line), 2007 (dotted-irregular line).

Precipitation conditions for the 1995–2008 period

Because precipitation is the main factor triggering both the geomorphic and edaphic activity at La Revilla area, we analyzed annual, seasonal, and daily rainfall data for the monitored period from the closest weather station (Matabuena, #2180 of the Spanish network, located 7 km south of the reclaimed quarry at a similar elevation, with records since 1936).

The precipitation analyses show that annual precipitation was highly variable during the 14 hydrologic-years covered in this study (Figure 13). This was generally less than the annual average 679·1 mm, with only 3 years exceeding the average. The driest year in a 72-year record is included in this period: 375·8 mm for 2004–2005.

Monthly precipitation totals confirm that the autumn-to-spring cycles of the 1997–1998 and 2002–2003 hydrological years include the only three wet monthly cycles of the monitored period (two consecutive months with more than 100 mm): cycle 1 – November 1997 (224 mm) and December 1997 (140 mm); cycle 2 – April 1998 (165 mm) and May 1998 (103 mm); cycle 3 – October 2002 (104 mm) and November 2002 (101 mm). These wet cycles coincide with the periods of mass movements at the highwall, which were

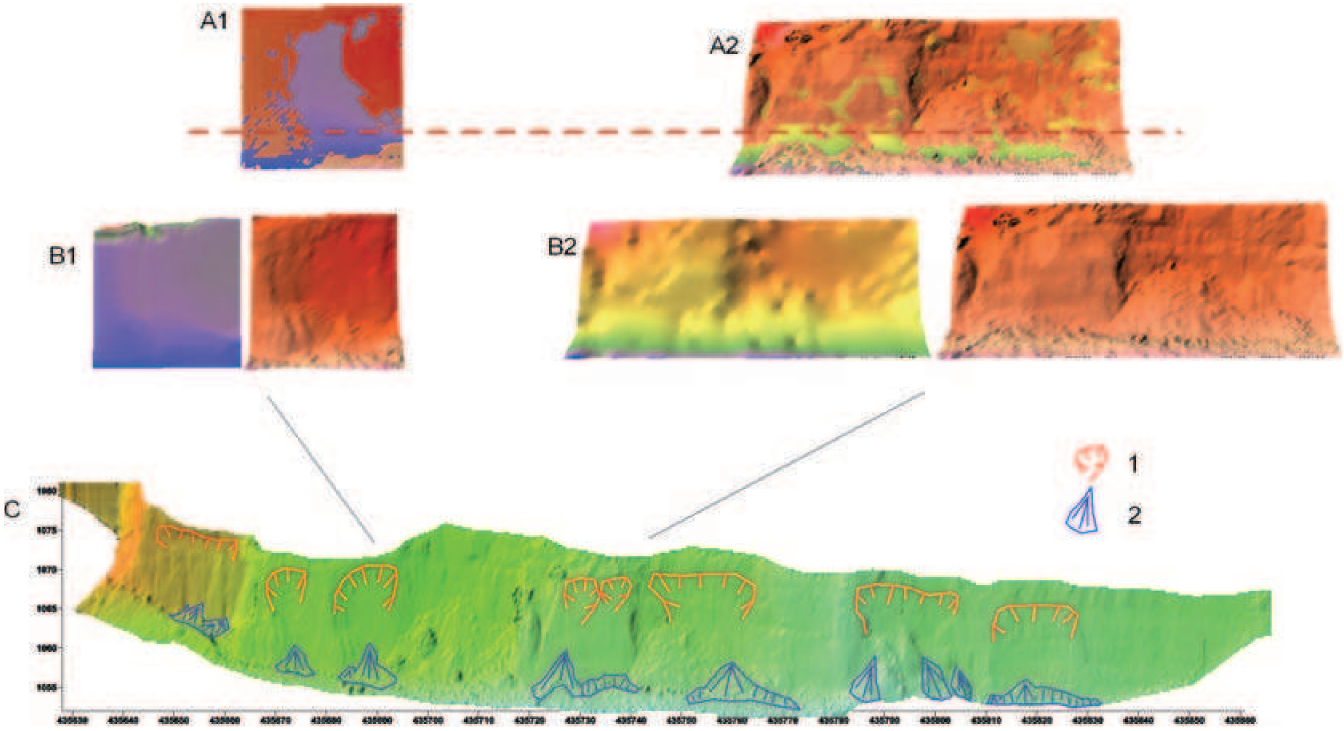

Figure 7. 2007 DEM of the highwall–trench sector, showing the main erosive (sand fall scars, 1) and depositional (sand slopes and cones, 2) features (figure C), and two examples of the 1995 and 2007 3-D comparisons (Figure A and B). B1 and B2 represent the 1995-interpreted (left) and 2007 (right) topographies of two locations on the highwall. Figure A1 and A2 show the superposition of those models; the broken line separates the domains of erosion (above the line, light purple in A1, orange in A2) and deposition (below the line, dark purple in A1, yellow-green in A2). X and z UTM coordinates, 30 zone.

Table IV. Percentage of bare soil on the reclaimed concave slope of La Revilla

Year 1997
Seven random plots

1	2	3	4	5	6	7
25	75	40	60	30	25	30

YEAR 2001

TRANSECT 1							TRANSECT 2							TRANSECT 3							TRANSECT 4						
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
60	15	40	40	0	15	0	40	15	15	15	0	15	90	15	40	15	0	15	15	15	60	15	5	10	15	0	10

YEAR 2002

TRANSECT 1							TRANSECT 2							TRANSECT 3							TRANSECT 4						
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
10	5	40	0	10	0	10	20	40	5	60	10	5	10	0	15	0	50	40	50	30	5	0	40	10	5	15	5

YEAR 2003

TRANSECT 1							TRANSECT 2							TRANSECT 3							TRANSECT 4						
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
10	0	15	30	10	15	25	20	20	0	20	10	5	15	25	10	15	10	30	30	20	40	0	30	0	10	0	20

YEAR 2004

TRANSECT 1							TRANSECT 2							TRANSECT 3							TRANSECT 4						
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
9	0	14	28	9	14	23	19	19	0	18	11	4	14	23	9	16	9	28	27	17	38	0	28	0	9	0	15

YEAR 2005

TRANSECT 1							TRANSECT 2							TRANSECT 3							TRANSECT 4						
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
16	4	17	21	22	13	23	15	23	3	19	15	6	18	25	10	19	21	30	27	12	25	5	26	0	11	0	18

YEAR 2006

TRANSECT 1							TRANSECT 2							TRANSECT 3							TRANSECT 4						
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
8	8	10	7	7	3	5	8	10	15	15	5	5	8	20	8	7	5	30	30	9	30	10	7	5	8	8	10

YEAR 2007

TRANSECT 1							TRANSECT 2							TRANSECT 3							TRANSECT 4						
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
10	8	15	10	5	10	15	10	15	8	15	0	5	20	5	5	10	0	30	20	5	3	0	0	5	20	0	0

YEAR 2008

TRANSECT 1							TRANSECT 2							TRANSECT 3							TRANSECT 4						
1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
5	5	0	5	0	0	0	20	0	0	3	5	5	10	0	0	5	8	5	0	8	3	5	5	8	5	0	10

Note: In each set of data, the first row is the plot number and the second is the percentage of bare soil.

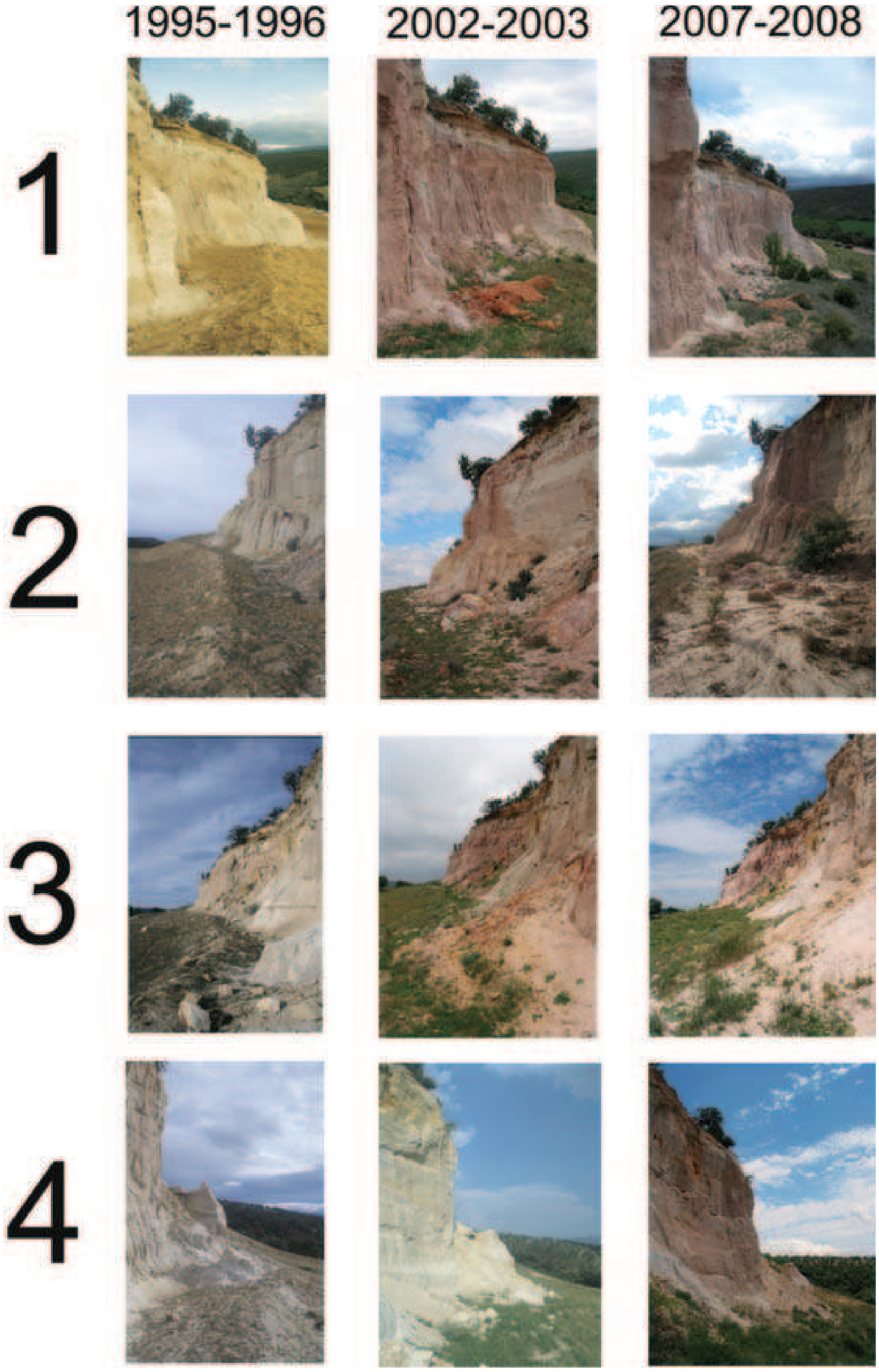

Figure 8. Comparison of four selected control points at different times of the monitored evolution of the highwall–trench sector: beginning (1995–1996), intermediate (2002–2003) and recent (2007–2008).

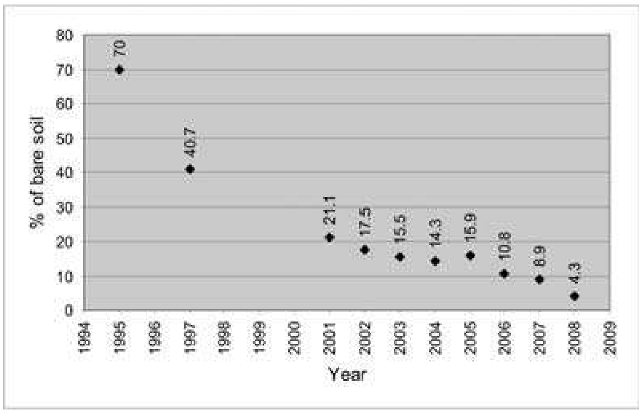

Figure 9. Rate of recovery for vegetation on the reconstructed concave slope from 1995 to 2008. The figure plots mean values from data of Table IV.

recorded after the autumn-to-spring cycles of 1997–1998 and 2002–2003.

Daily precipitation for the period showed a maximum of 78·2 mm in 6 January 1996. The magnitude and frequency curve of the monthly maximum daily precipitation for each year indicates that this value of 78·2 mm corresponds to a 17-year return period (5·9% probability of occurrence) (Figure 14). These data are in close agreement (22-year return period, 4·5% probability) with a software application that calculates return periods of daily maximum precipitation for any site on the peninsular Spain (MF, 1999).

However, because of its occurrence in January, this 78·2 mm relatively high magnitude and low frequency event had no high intensity. Indeed, the rainfall intensity at the automatic rain gauge closest to Matabuena (Segovia) was 9·2 mm h^{-1}, which corresponds to a moderate intensity according to the Spanish Meteorological Agency (AEMET). A survey of the

Table V. Comparison between mean values of several edaphic indicators measured in different spatial-temporal locations related to the La Revilla reclaimed quarried slope. SD – Standard Deviation

Soils	o.m. (%)		C/N		P_2O_5 (mg/100 g)		Exchangeable base cations (mg/100 g)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
'Natural' or 'historic' soils of the surroundings of La Revilla quarry	?		?		?		?	
Soils adjacent to the quarry, (1995 analysis), equivalent to those removed by mining	4·64	1·79	14·78	1·38	17·79	26·02	265·80	96·01
Barren carbonatic colluvium (1995 analysis) soil substratum	0·32	0·08	15·07	4·69	9·83	1·04	247·87	53·84
Soils of the reclaimed area (1998 analysis)	0·76	0·32	11·68	3·28	13·44	7·58	869·66	98·73
Soils of the reclaimed area (2002 analysis)	1·41	0·46	13·39	3·48	20·73	16·62	510·73	73·53
Soils of the reclaimed area (2005 analysis)	1·93	0·77	13·21	1·56	23·59	15·67	440·26	44·18
Soils of the reclaimed area (2008 analysis)	1·99	0·52	10·81	1·58	19·41	7·33	337·81	92·47

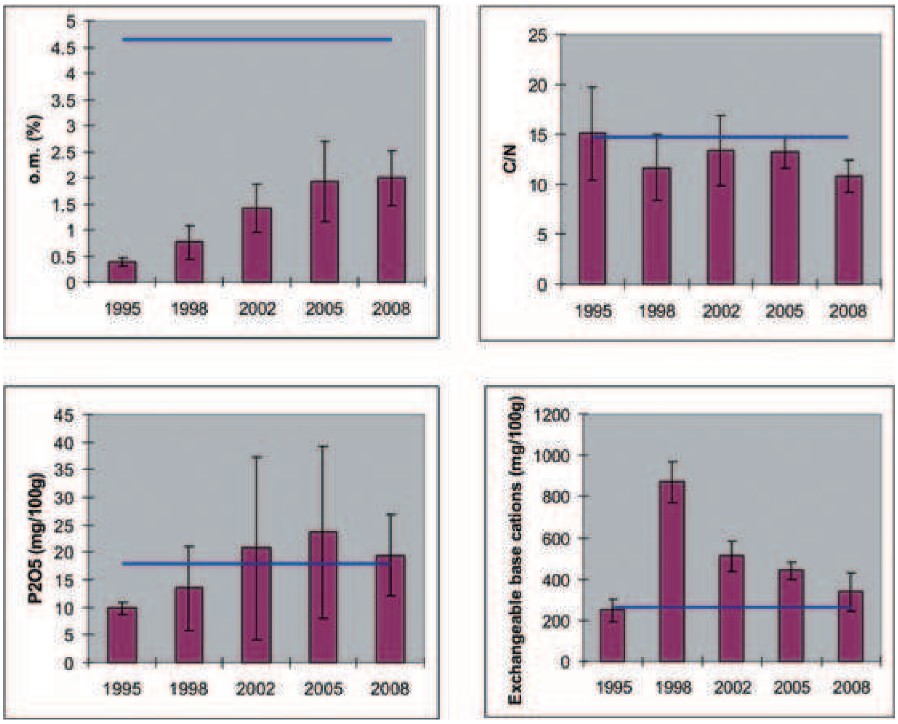

Figure 10. Evolution of mean values of edaphic indicators of the reclaimed area from 1995 to 2008, compared with mean values of the same edaphic indicators of soils adjacent to the quarry (horizontal line, from 1995 analysis), equivalent to those removed by mining. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table VI. Comparison of mean values of assimilable phosphorus (P_2O_5) between the upper and lower sectors of the concave reclaimed slope (Figure 4 shows the location of the samples)

	Upper slope		Mean P_2O_5 mg/100 g			
Sample code	X-UTM	Y-UTM	1998	2002	2005	2008
LR4W	435646	4556658	10·40	11·50	17·00	16·20
LR3W	435641	4556653				
LR2W	435640	4556640				
LR3C	435712	4556634				
LR2E	435777	4556635				
	Lower slope		Mean P_2O_5 mg/100 g			
Sample code	X-UTM	Y-UTM	1998	2002	2005	2008
LR1W	435635	4556625	16·67	33·00	34·67	25·33
LR2C	435712	4556621				
LR1E	435777	4556614				
			Δ P_2O_5 +60·29 %	Δ P_2O_5 +286·96 %	Δ P_2O_5 +103·94 %	Δ P_2O_5 +56·36 %

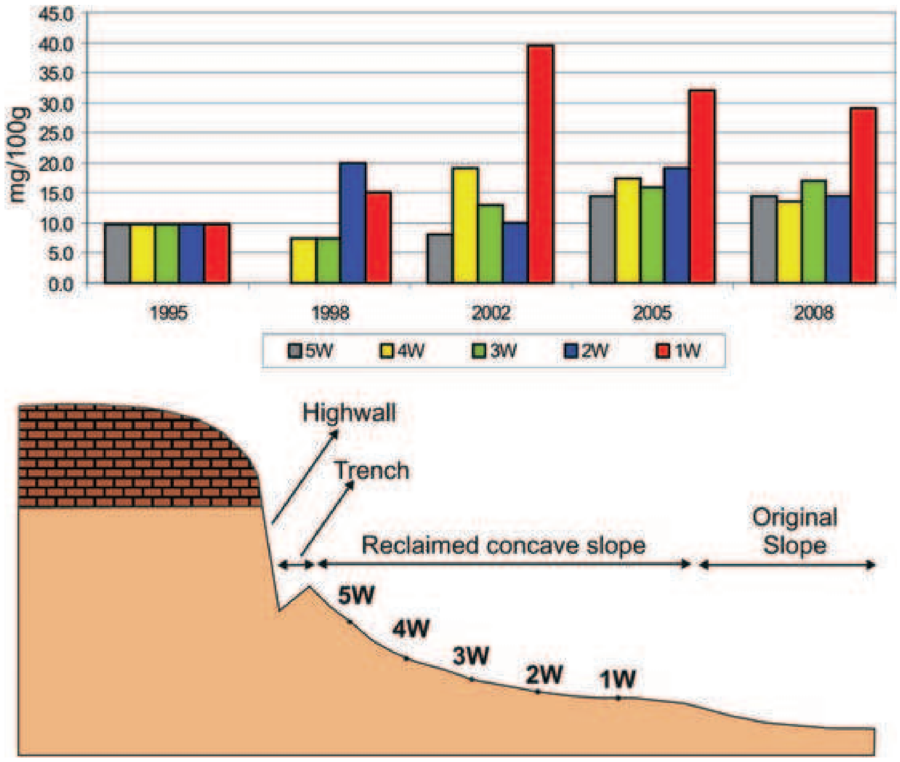

Figure 11. Variation of assimilable phosphorus (P_2O_5) with slope, through time, denotes a recovery of subsurficial hydrological processes, with its accumulation at the toe of the slope. It has to be considered that after the measurement of 1995, the reclaimed concave slope was fertilized with a complex fertilizer in proportions 12/36/12 (NPK) at 600 kg ha^{-1}.

Table VII. Comparison of mean values of organic matter (o.m.) between upper and lower sectors of the concave reclaimed slope (Figure 4 shows the location of the samples)

	Upper slope		organic matter (o.m.) (%)			
Sample code	X-UTM	Y-UTM	1998	2002	2005	2008
LR4W	435646	4556658	0·64	1·47	1·98	2·07
LR3W	435641	4556653				
LR2W	435640	4556640				
LR3C	435712	4556634				
LR2E	435777	4556635				
	Lower slope		organic matter (o.m.) (%)			
Sample code	X-UTM	Y-UTM	1998	2002	2005	2008
LR1W	435635	4556625	0·96	1·20	2·48	2·28
LR2C	435712	4556621				
LR1E	435777	4556614				
			Δ o.m.= + 50·00 %	Δ o.m. –18·37 %	Δ o.m. +25·25 %	Δ o.m. +10·14 %

weather conditions for 6 January 1996, shows that the frontal precipitation system was homogeneous between Segovia and Matabuena.

Extreme rainfall events typically take place in this region as a result of summer convective storms (occurring from May through September). The maximum daily precipitation for those months during the monitored period (1995–2008) was 35·6 mm, with a 1·25-year return period (80% of probability). As a result, it can be concluded that no intense summer convective storms occurred during this period.

Discussion

Comparison of the 1995 and 2007 topographies and of the ground photo survey illustrate that the geomorphological evolution of the highwall–trench sector is occurring as it was initially predicted – the highwall is being eroded, and the moved material is being accumulated at the trench, without interfering with the recovery of soils and vegetation on the concave slope. However, the trench is near its retention capacity, and is being filled faster than planned (see

Table VIII. Multiple range tests for organic matter

		Percentage organic matter (o.m.)		
Sampling year	Number of samples	Mean	Standard deviation	Homogeneous groups
1998	8	0·76	0·32	a
2002	11	1·41	0·46	b
2005	11	1·93	0·77	c
2008	11	1·99	0·52	c

Comparison	Difference	+/– Limits
1998 vs 2002	*–0·65	0·53
1998 vs 2005	*–1·17	0·53
1998 vs 2008	*–1·23	0·53
2002 vs 2005	*–0·52	0·49
2002 vs 2008	*–0·58	0·49
2005 vs 2008	*–0·06	0·49

* Denotes a statistically significant difference at the 95% confidence level.

Table IX. Multiple range test for exchangeable base cations

		Exchangeable base cations (mg/100 g)		
Sampling year	Number of samples	Mean	Standard deviation	Homogeneous groups
2008	11	337·81	92·47	a
2005	11	440·26	44·18	b
2002	11	510·73	73·53	c
1998	8	869·66	93·01	d

Comparison	Difference	+/– Limits
1998 vs 2002	*358·94	73·80
1998 vs 2005	*429·42	73·80
1998 vs 2008	*531·85	73·80
2002 vs 2005	*70·48	67·72
2002 vs 2008	*172·92	67·72
2005 vs 2008	*102·44	67·72

* Denotes a statistical significant difference at the 95% confidence level.

Martín-Duque *et al.*, 1998). This fact clearly points to the need for an integrated 3D drainage network for similar reclamation situations, as will be detailed in the conclusions.

The soil cover analysis shows that soil formation processes clearly predominate over the concave slope. Additional field observations show that important biomass accumulation on the rehabilitated surface is being produced by the existing vegetation cover. The absence of hydric erosion processes on the reconstructed concave slope can be interpreted as a consequence of its inherent high stability, due to the energy-dissipating properties of a reduction in the gradient downslope. Consequently, the geomorphic stability has allowed the effectiveness of the edaphogenesis and vegetation development processes. The geomorphic stability of the concave slope is in agreement with other studies in reclaimed lands (Hancock *et al.*, 2003; Toy and Chuse, 2005).

The soil quality analysis monitoring confirms, mainly through the increase in organic matter, that edaphogenic processes are dominant and widespread in the whole reclaimed concave slope, as predicted by the geomorphic approach to the reclamation.

The difference in assimilable phosphorus between the upper and lower sectors of the concave reclaimed slope – with a positive variation in the downslope direction – is interpreted as a recovery of the subsurficial hydrologic dynamic in the reclaimed concave slope. The decreasing of exchangeable base cations can indicate either a leaching process or their use as nutrients by constantly increasing vegetation cover.

The visual evolution of the reclaimed area, as shown in the oblique aerial photo survey (Figure 12) evidence a trend towards the re-establishment of the landscape conditions of the surrounding area, reflecting the recovery of the area's natural geomorphic and ecological processes.

The precipitation data showing a drier-than-average period suggests that the geomorphic evolution of La Revilla for the period from the spring of 1995 to the spring of 2008 can be considered of 'minimal evolution'. Monthly precipitation totals suggest that wet cycles within the autumn-to-spring periods of 1997–1998 and 2002–2003 are most likely responsible for triggering the observed mass movements at the highwall, recorded in June 1998 and June 2003. Therefore, more frequent maximum precipitations in long intervals (wet monthly cycles) would be expected to accelerate the highwall geomorphic evolution by mass movements. Intense summer convective storms would considerably accelerate the geomorphic evolution of the highwall–trench sector by hydric erosion. Indeed, major geomorphic effects of such storms in nearby areas have been documented by Lucía *et al.* (2008). However, because none of these events occurred in the area within the monitored period, it is not possible to extrapolate the geomorphic evolution from the period of record to a longer context.

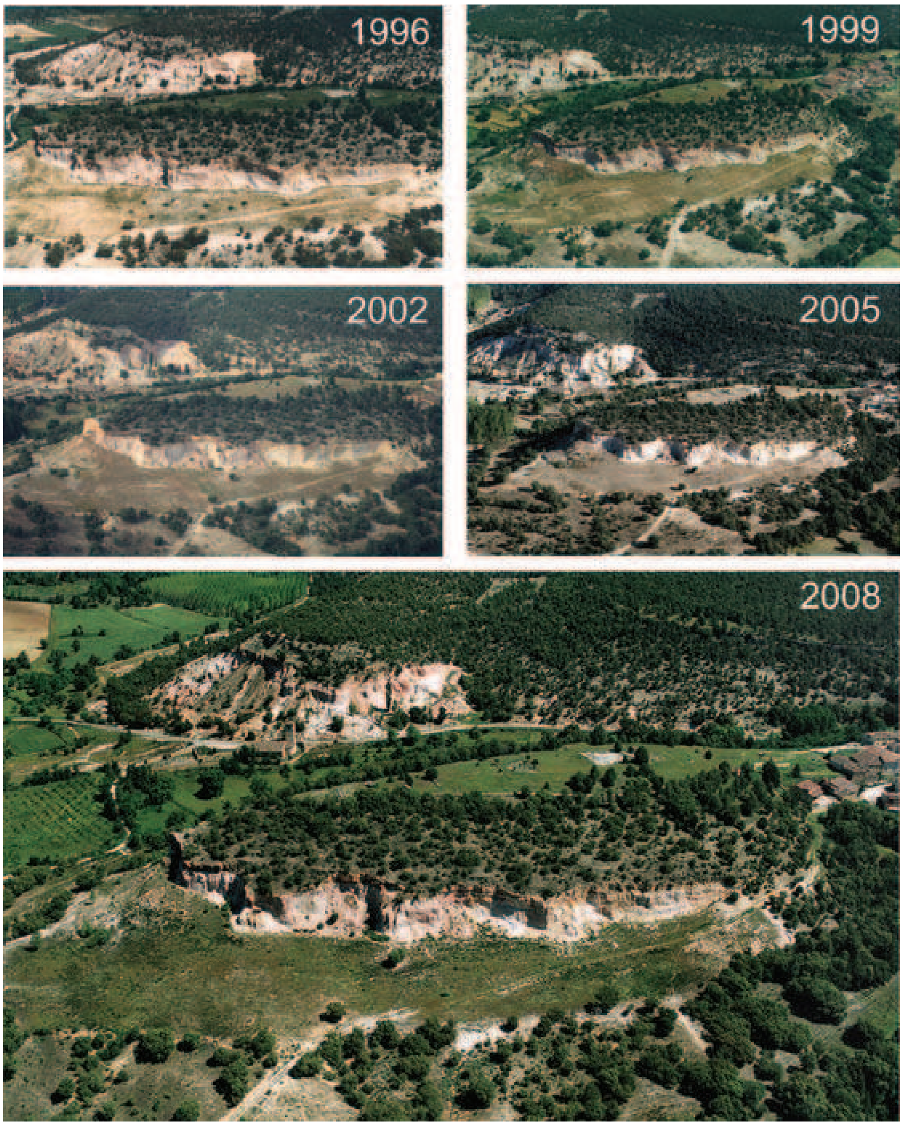

Figure 12. Temporal series of oblique aerial photos (Paisajes Españoles S.A.) of the La Revilla quarried slope reclamation to present.

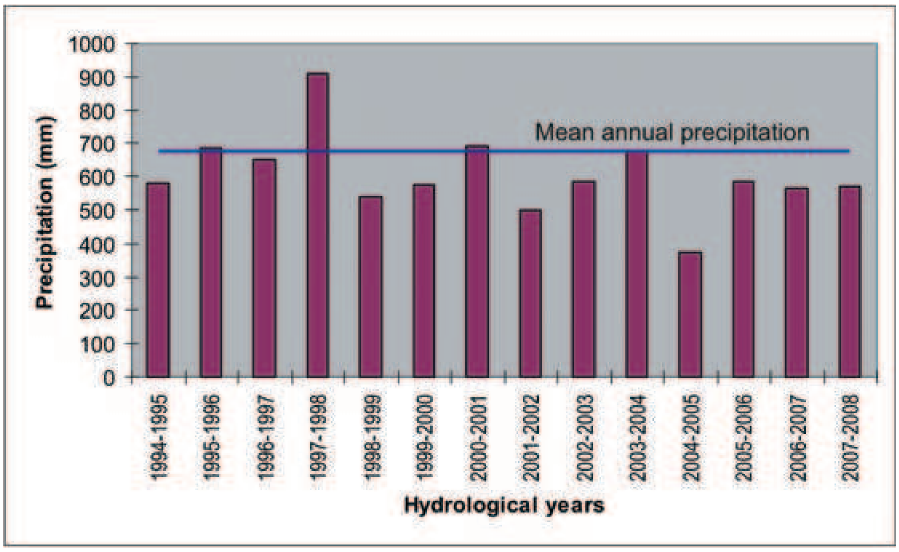

Figure 13. Precipitation at the reclaimed area from the 1994–1995 to the 2007–2008 hydrological years. This figure is available in colour online at www.interscience.wiley.com/journal/espl

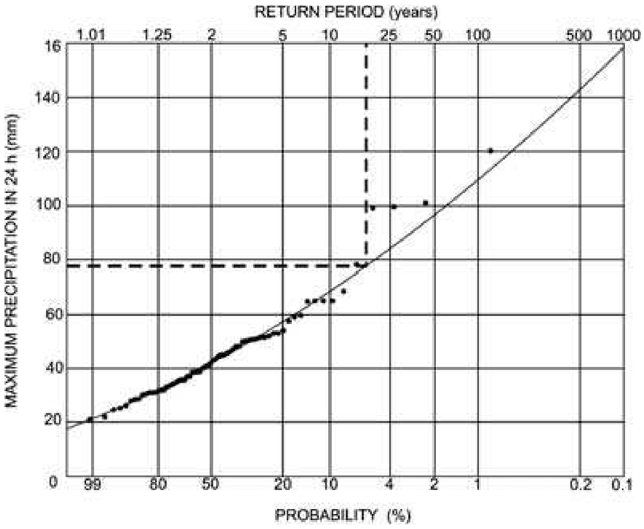

Figure 14. Magnitude and frequency SQRT curve for the Matabuena weather station (1936–2008), showing (dashed line) the maximum daily precipitation that occurred within the monitored period (1995–2008).

Conclusions

The objective of the geomorphic approach to La Revilla reclamation was to re-establish an approximate dynamic equilibrium between processes and landforms. The aim of the highwall–trench–concave slope model was to manage the geomorphic processes through the reconstruction of specific landforms. As a tool to restore geomorphic processes, the landform design included not only a topographical reconstruction, but also the reposition of surficial deposits in thicknesses that adapt to natural analogues, because these surficial deposits greatly affect hydrologic and edaphic processes.

The 13-year evolution of the highwall–trench–concave slope geomorphic model executed at La Revilla reclaimed quarried slope provides a scenario of recuperation of geomorphological, hydrological and edaphic functions and processes.

Arguably, the most original idea of the geomorphic design described is the highwall–trench sector, in which the highwall is ‘allowed to mature naturally’. This is cost-effective, as it eliminates a need for long-term maintenance (see Figure 15). Depending on slope erosion to achieve the stability of a naturally-occurring equilibrium profile is an approach that is not commonly considered in land reclamation. The design does not reproduce the original contour (sigmoid), but sets the stage for it to form in the long term. This may seem counterintuitive to many typical reclamation protocols and regulations, in which highwall elimination is required.

In our model, the convex part of the slope is not reconstructed, but allowed to evolve naturally, forming in the long term a convex–straight–talus–concave slope by natural processes. The model from La Revilla goes further than the concept of stability. It deals with managing the dynamic disequilibrium and geomorphic dynamics of the slopes. In this approach, geomorphic processes have been allowed ‘to behave as they should’.

The fact that the trench is being filled faster than planned shows a deficiency in the sizing of the model, and that deeper trenches are needed for this type of silica sand quarry reclamation. Since the model only functions well if the trench is not full, the quantification of the slope evolution for any future application is a key issue. In this regard, the 13-year monitoring of this highwall evolution – as a response to the distribution of the rainfall conditions for the same period – constitutes invaluable data for regional extrapolation, countering the difficulty and high degree of uncertainty of obtaining that information from theoretical slope models.

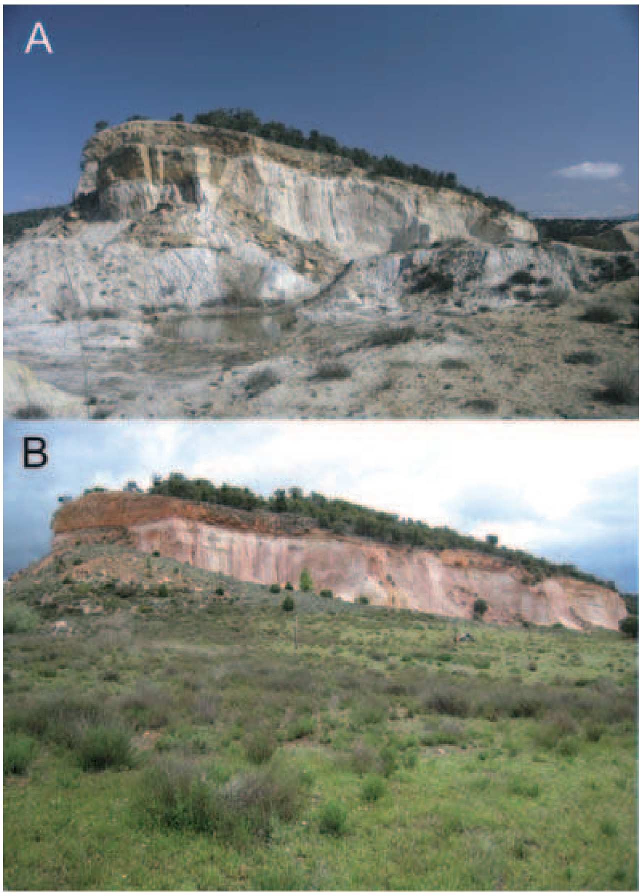

Figure 15. The recovery of vegetation and soils at the reconstructed concave slope and the evolution of the highwall–trench sector have occurred without any maintenance. (A) 1995; (B) 2007.

We must consider, finally, that this geomorphic reclamation slope model was designed as two-dimensional (at a slope scale), because of the small size of the quarry. Therefore, it can be considered as a useful component to be included in larger 3D geomorphic reclamation designs of contour mining and quarried slope scenarios. Arguably, a combination of this hillslope profile model with the construction of an integrated 3D drainage network, breaking the reclaimed area into several watersheds with stream channels perpendicular to the highwall (Measles and Bugosh, 2007), should be an optimum model for geomorphic reclamation of contour mining and quarried slopes, because it considers drainage management as well as slope evolution. A combination of geomorphic hillslope models with integrated geomorphic drainage management has been completed at several sites in the USA since 2000 (Bugosh, 2000, 2002, 2004, 2006a). Besides, as a lesson learned at La Revilla, a specific combination of the highwall–trench–concave slope model with an integrated 3D drainage network has been executed in other slope quarry reclamations of Central Spain since 2008.

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