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A geomorphological design for the rehabilitation of an abandoned sand quarry in central Spain

J.F. Martín Duque[a,*], J. Pedraza[a], A. Díez[b], M.A. Sanz[a], R.M. Carrasco[b]

[a] Department of Geodynamics, Faculty of Geology, Universidad Complutense, Ciudad Universitaria s/n, 28040 Madrid, Spain
[b] Department of Environment, Faculty of Sciences, Universidad Europea de Madrid, Villaviciosa de Odón, 28670 Madrid, Spain

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Abstract

The article describes, how a geomorphological design based on the original relief architecture (prior to exploitation), can contribute to the ecological and landscape reclamation of an environment affected by a silica sand quarry located in the central area of the Iberian Peninsula (Spain). The reclamation procedure based on this design gives considerable importance to integral geomorphological criteria (morphographic, morphodynamic and morphoevolutionary); this approach is designed to complete the methodologies applied in landscape restorations, by incorporating aspects of morphogenetic dynamics in addition to the already habitual aspects based on geometrical criteria. This proposal also gives rise to a discussion regarding the philosophy underlying environmental and landscape restorations, which often attach too much importance to revegetation processes or to strictly aesthetic considerations without taking into account the long-term evolution of natural systems, which is chiefly regulated by geomorphoedaphic processes.

Keywords: Restoration; Landscape; Environmental geomorphology

1. Introduction

There is a little tradition in Spain of restorations of sites affected by mining activities. The first legislation in this connection appeared in 1982, since which year application for opening of mining projects should be accompanied by a mandatory Restoration Plan. However, companies operating mines which were active prior to 1982 have no obligation, whatsoever with respect to land restoration. Consequently, certain Spanish regional authorities have launched projects for the rehabilitation of old mines and quarries, many of which are now closed; the 'La Revilla' quarry addressed in this article came into this category.

In the region in which 'La Revilla' is located there are many other quarries, both abandoned and operational, with similar features. Although, the environmental effects of each of these are scant, their combined impact is considerable due to the fact that they are widely scattered over the region. This is due to several reasons: they are, generally speaking, small quarries with an extremely short average life ('contour mining' which makes use of natural scarps and taluses using light machinery), which means that, new quarries are constantly being opened and old ones being abandoned; the activity has been carried on in the area for several centuries and has increased considerably in

*Corresponding author. Tel.: +34 91 3944857; fax: +34 91 394 4845.

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recent years, mainly due to the demand resulting from the expansion and industrial activity of a large city such as Madrid.

Considering the problem as a whole and the high quality of the affected landscape, we commenced a project designed to establish reclamation criteria applicable to all the slopes affected by sand extraction; the first stage of this project was the reclamation of 'La Revilla'.

2. Factors affecting the rehabilitation

2.1. Environment

The quarry of La Revilla, now closed down, is located in the centre of the Iberian Peninsula, on the northern foot of the Guadarrama Mountains, which is part of the Spanish Central System mountain range (Fig. 1).

From a geomorphological standpoint, the quarry was located on one side of a small meseta type residual relief, which has evolved on silica sands at the base (the material extracted from the mine) and limestone and dolomite rocks at the top. The average altitude of the area ranges between 1000 and 1100 m above sea level.

The climate can be classified as: Mesothermal type, Mediterranean subtype, and temperate-cool variety (in the Koeppen climate classification system). The average annual temperature is 10°C. The average period of frosts lasts from 6 to 8 months. Average annual precipitation is 550 mm, and rainfall mainly occurs from October to May. The mean annual water deficit is between 100 and 400 mm.

The soils which have evolved on dolomitic bedrock and carbonate type colluvium, are calcaric cambisols in areas with low and moderate gradients and rendzic leptosols in areas with steeper gradients. The soils which have formed at the expense of acid substrata (sands and clays) and low moderate gradients are albic arenosols, and even haplic luvisols.

The natural vegetation in the terrains on basic substratum is dense woodland consisting of white savin juniper (*Juniperus thurifera*) and holm oak (*Quercus ilex*, subsp. *ballota*), accompanied by juniper (*Juniperus communis* subsp. *hemisphaerica*). Holm oak woods are dominant on acid substrata (sands). However, the mosaic making up the current vegetation cover is the result of ancestral human activity: deforestation linked to livestock activities and, to a lesser extent, farming activities, leading to the formation of low woodland masses, scrub, and grazing land.

2.2. Features of the abandoned quarry (environmental impacts)

The 'La Revilla' silica sand quarry was a small and longitudinal open pit which developed by successive levelling of the southern side of a small meseta type relief (contour mining). After mining the pit had: a vertical face, 15 m high on average; a pit floor, with an average width of 40 m; and numerous spoils piles, usually on the outside of the pit floor (Fig. 2). Extraction was intermittent and of low intensity, and only 110 000 m^3 of material was exploited in the years in which the quarry was operational. Extraction of the sand commenced in 1965 and the quarry was active until the early 1980s, when it was abandoned due to technical difficulties and to pressure from the community prompted by the outstanding nature of the ecology and landscape of the area.

This extraction led to a series of negative environmental impacts, which were described and appraised using standardized methodologies (Leopold et al., 1971; González Alonso et al., 1991); thus:

- The effects on the landscape were evaluated as critical: the changes to the original morphology and vegetation, introduced profound contrasts and lack of harmony in an environment with high-quality landscape.
- The impacts on surface water were evaluated as severe: the alterations to its dynamics and to the drainage network, caused an increase in runoff, erosion, and increased the turbidity downstream.
- The impacts on the soil and vegetation were also evaluated as severe. With respect to the soil, the removal of the original edaphic cover led to erosion and degradation in the surrounding area; with respect to vegetation and soil uses, the destruction of the original cover (grazing land, replacement scrub and trees) and the reduction in forested surface and pastureland, decreased the possibilities of using the location as a nature site.

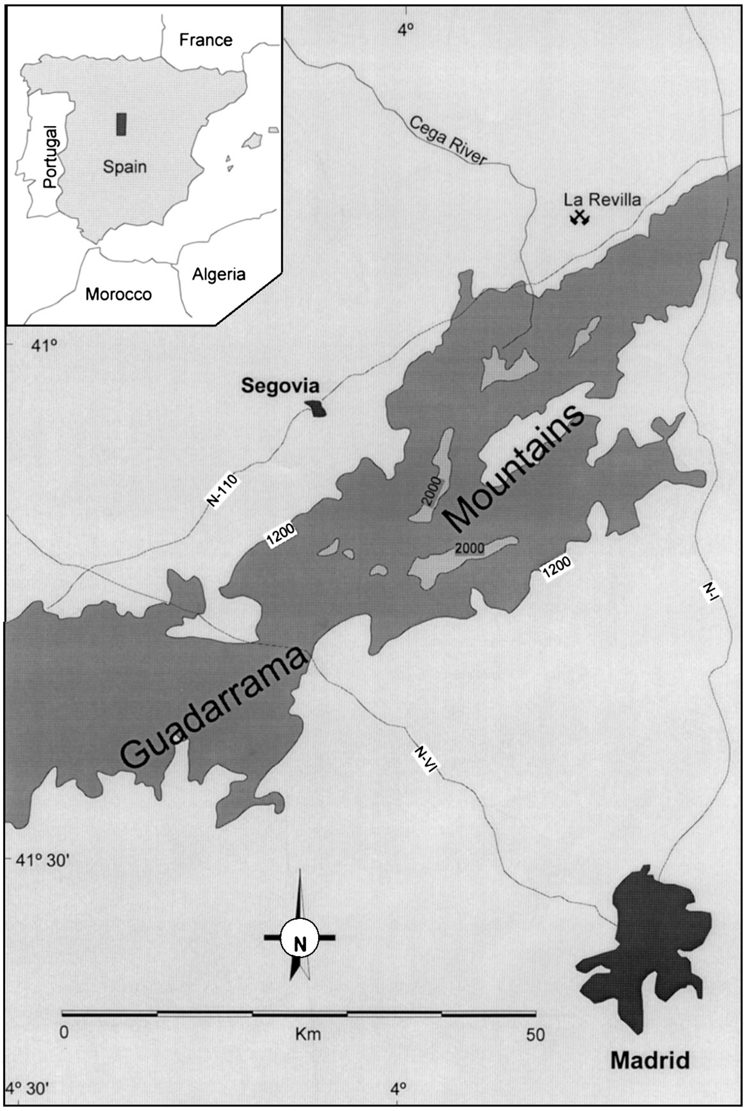

Fig. 1. The location of the 'La Revilla' quarry.

- The alterations to the initial topography affect the dynamics of the groundwater, leading to the dissection of small permeable levels and to diffuse flows or seeping on the former quarry face. Since, the resources were of scant interest, the alteration to them was not significant; however, considerable disturbance was caused by the fact that these springs perforated the sands and led to major gravitational processes (landslides, falls) on the old quarry face (see Fig. 2).

The effects leading to intense water erosion on the surface directly affected by the mining operations (the quarry face, the quarry site and the barren spoils piles), the formation of rills, gullies and pipes, in addition to the sedimentation produced on the land located on the versant below the former quarry, were also classified as severe.

Fig. 2. General view of the west sector of the quarry prior to the rehabilitation: dispersed spoils banks affected by erosion processes, falling of blocks from the abandoned quarry face and significant impact on the ecology and landscape.

2.3. End use of the land to be restored and technical and economic determining factors

As indicated earlier, mining in this area is practically an artisan activity. There is no dominating mining economy and, consequently, extraction activities have been subordinated to farming and forestry and the area retains a markedly rural character. Consequently, biophysical and socioeconomic factors were a priority when selecting an appropriate potential use for the site: the traditional natural, forestry and grazing uses of the region were considered to be the most appropriate; these could be combined harmoniously with leisure and low-density recreational activities.

In addition, introducing the selected use led us to implement a reclamation project adapted as far as possible to the natural dynamics of the terrain: we consider that the geomorphological design executed meets this goal and may have a contribution to make to projects of this type.

Last but not least, the final design was also determined by other factors: a low budget, and the scant volume of spoils available for use in rehabilitation (insufficient spoil to refill pit).

3. The geomorphological design

3.1. Objectives

Based on the above determining factors, the ultimate objective was to lay the groundwork for the natural regeneration of a system capable of replacing the functions of the forest mass/grazing land (holm oak and savin juniper) on carbonate soils. For this purpose it was necessary to

- Generate a morphology in harmony with that of the surroundings, capable of reestablishing the potential geomorphological processes.
- Establish a hydrological balance. That of the site was altered prior to the mining operations and exaggerated by the mining activity.
- Promote soil formation and evolution (edaphogenesis-biostasia) to create a substratum of biotic activity.
- Establish an initial vegetation cover and create the conditions for this cover to develop alone, either naturally or within a forestry and pastureland system, into a formation with similar features to those of the original vegetation.

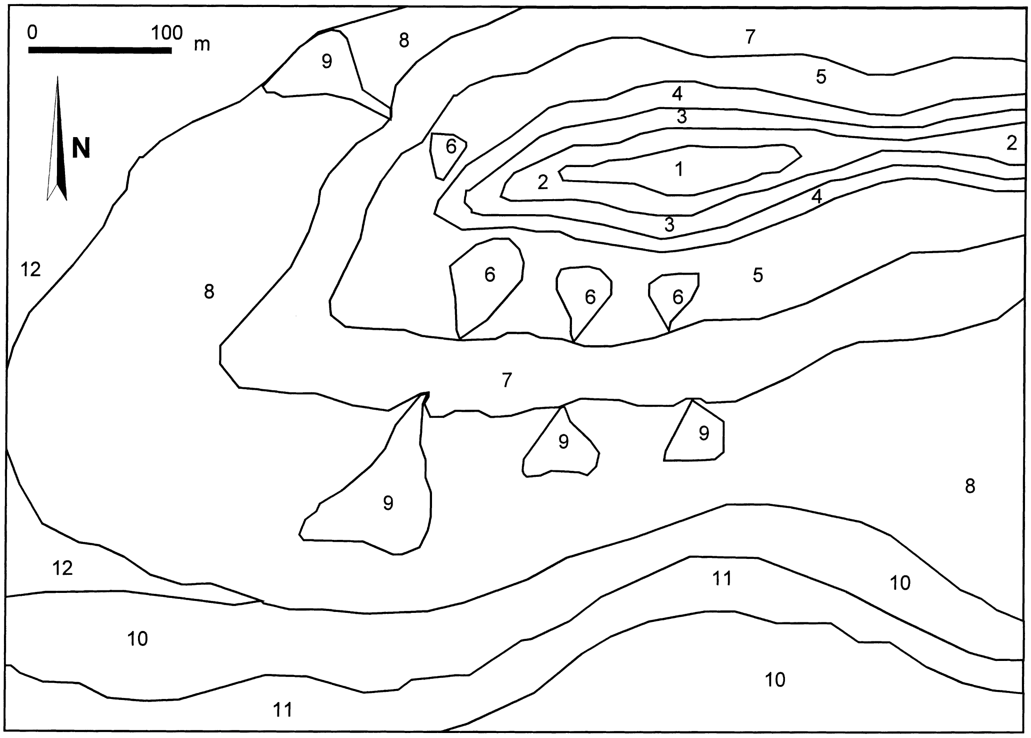

Fig. 3. Map of the geomorphological units in the area around the 'La Revilla' quarry. The working of this quarry affected units 5, 6, 7, 8 and 9. The description and features of each unit are supplied in Table 1.

Based on these premises, the project's main objective can be summarized as follows: to use the available spoils to design a morphology capable of adapting to the geomorphological evolutionary trends of the area, so that restoration would to a great extent occur naturally.

The study, therefore, differs from the approach taken in many restoration projects, in which the long-term natural evolution is not taken into consideration. Many of these cases demonstrate that, unless the geometrical designs (taluses, berms, etc.) are maintained artificially, the geomorphology dynamics ultimately prevail and the rehabilitated areas evolve naturally and, consequently, not always with the desired results.

3.2. Geomorphological study as a starting point

The first step was to conduct an analysis of the origin and evolution of the landforms in the area. The quarry was located on the sides of a small residual meseta type relief. Natural gullies are frequent, in most cases increased by extraction activities and by ploughing in the past. The surfaces of the versants are covered with colluvium formations of fine (loamy) granulometry and with levels of coarser formations (gravel); they have formed at the expense of the dolomites lying on the sands.

The findings of this study were shown in a map of geomorphological units (Fig. 3). The latter were shown (Table 1) in morphological and dynamic terms (active geomorphological and edaphic processes and evolutionary trends). This form of classification and characterization of the relief is based on work such as, that carried out by Dalrymple et al. (1968) and Godfrey and Cleaves (1991). These authors carried out landscape classifications in landform units, characterizing each of these units in terms of contemporary geomorphological and edaphic processes; this concept of classification and description was invaluable to our

Table 1
Description of the geomorphological units mapped in Fig. 3

Unit 1	Infiltration surface. Very slightly convex, with a gradient of between 0° and 4°. Dominant edaphic processes related to the migration of water and materials on the subsoil vertical
Unit 2	Infiltration slope. Slightly convex slope, with gradients of between 4° and 11°. Dominant edaphic processes due to the vertical movement of water in the soil; lateral movements are beginning to occur in the subsoil on the higher gradients
Unit 3	Creep slope. Clearly convex, with gradients of between 11° and 25°. Lateral washing and concentrated runoff dominate
Unit 4	Fall face. Gradients of between 50° and 70°, the most common value being 65° (cliff). Characterised by the exposure of the parent material (dolomitic limestones) and the general absence of soil and vegetation. The dominant geomorphic process is considered to be fall
Unit 5	Debris slope. Straight. Gradients of between 15° and 35°, the most common being around 25°. This is basically an area of redeposition of the material from the abandoned quarry face, usually through mass movements
Unit 6	Gully scarp. Gradients of over 45°, with intense erosion of the concentrated stream channel. This is the most active unit in terms of water erosion, and, consequently, the edaphic processes are nonexistent
Unit 7	Colluvial footslope. Straight or slightly concave slope with gradients of 11°–15°. Deposition of material through mixed gravitational and flooding processes, forming a colluvium
Unit 8	Sheet flood glacis. Slope with concave profile and gradients of between 4° and 11°. Edaphic processes caused by vertical and lateral movements within the soil dominate, as do sheet floods
Unit 9	Alluvial cones. Slightly convex profile and gradients of between 4° and 15°. Depositing of stream material from unit 6; after the sporadic episodes in which they are functional, they suffer from rapid vegetation colonization
Unit 10	Floodplain. Virtually horizontal morphometrical profile, almost exclusively with edaphogenesis processes. Sporadic fluvial deposition phenomena
Unit 11	Riverbed, channel. This area is subject to migration of the main channel and, consequently, to geomorphological phenomena directly related to the functioning of the main current
Unit 12	Seep depression. They occupy the distal areas of the glacis, in which the finest matter from the slopes accumulate. Due to their nature, swamping and hydromorphism phenomena are frequent

planned rehabilitation, and involved simply establishing the morphometric (gradient) scales in which the different processes for this region take place.

3.3. The design of the slope profile

The geomorphological study (see Fig. 3) provided the basis for a rehabilitation design, which in the long term, would lead to reconstruction of a slope profile similar to that of the slopes in the area, i.e. reestablish the conditions in which the original elements of the landscape could form.

The final profile should be capable of controlling the runoff processes and the evolution of the gravitational processes at the abandoned quarry face. To meet this second objective, the design should include a trench at the footslope of the abandoned quarry face in order to retain the material fallen from the scarp. In addition, in time a slope morphology was to be designed following a general convex-straight-concave sequence, recognised as an equilibrium morphology in most environmental conditions (Toy and Hadley, 1987), including those of the region in question as analysed in the geomorphological study. More specifically, the slope sequence to be obtained was convex versant, scarp or cliff edge, talus consisting of debris slope, colluvium, and glacis.

The specific position of the profile to be reconstructed depended on the quantification of the available spoils. To this end a detailed contour map was prepared, 1:500, with one metre equidistance between the isohypses (or contours) of the area affected by the quarry (Fig. 4).

The optimum arrangement of the spoils for the reconstruction of the desired morphology was obtained by geometrical calculations (Fig. 5). The extrapolation of the profile for the surface as a whole, enabled us to ascertain the volume of usable spoils and their new placing as landfill according to the planned morphology. Once, we had the landfill arrangement we could obtain the topography to be reconstructed (Fig. 6); this topography is that established by the primary conditions required to ensure that the slope evolves into its natural profile, which as shown by the geomorphological study (see Fig. 3), comprises several elements (Fig. 7).

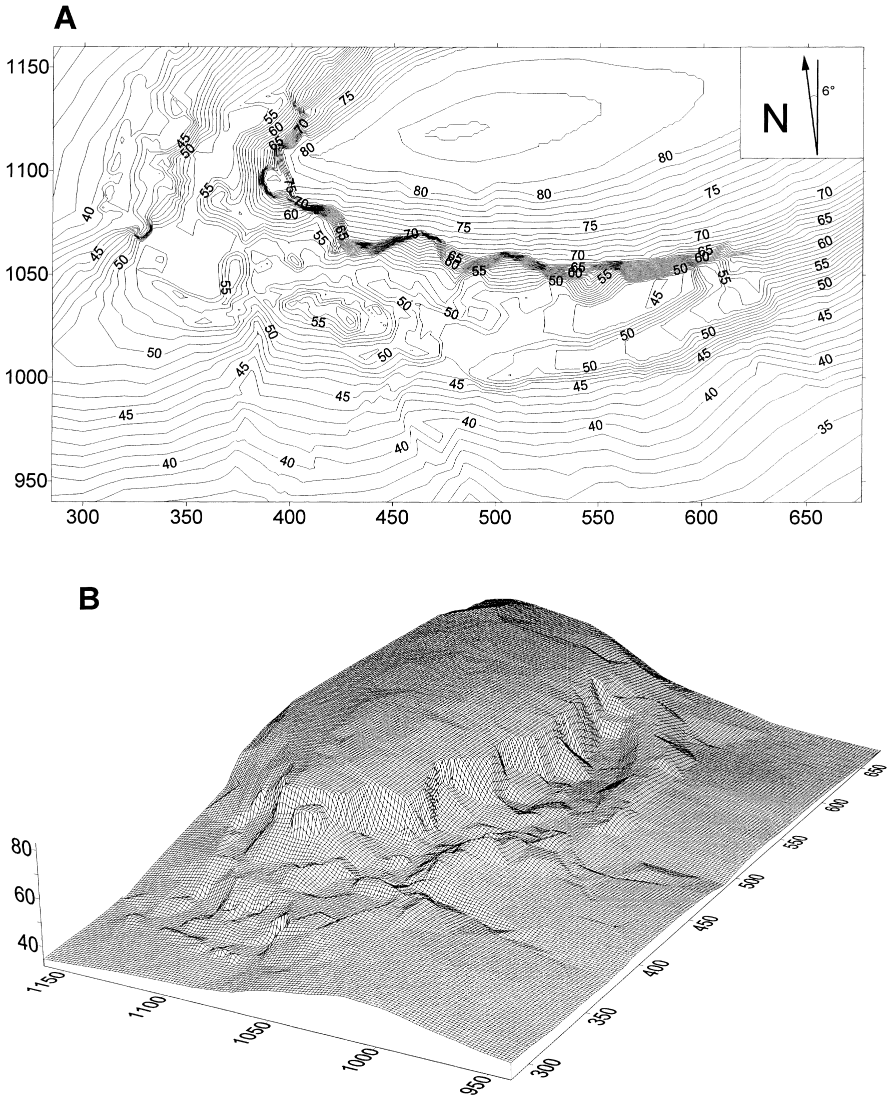

Fig. 4. Situation of the abandoned quarry prior to operations. A: contour map. B: block diagram of affected area, seen from the SW (SURFER 5.1 program). Distances in metres.

4. Soil and revegetation

Once the geomorphological design for optimizing the spoils and providing the appropriate slope profile had been executed, it was necessary to ascertain the physical and chemical attributes of the different materials involved in the rehabilitation, also in order to optimize the edaphic potential and to select the revegetation species. The necessary data were obtained through laboratory analysis of: soil from the original slope, surface deposits (colluvium) and sand spoils; the data are summarized in Table 2.

The spoils from the extraction activity, which were to be used to reconstruct the new topography were mainly sandy in texture and with an extremely low proportion of fines. As regards their chemical properties, their pH was neutral, with an extremely low organic matter content; nutrients were practically and toxicity nonexistent.

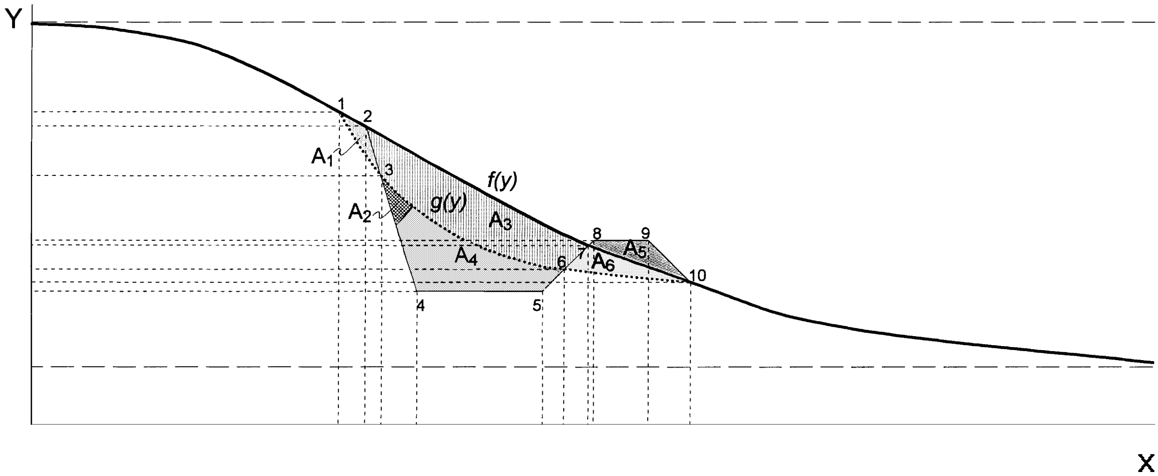

Fig. 5. Geometrical (two-dimensional) design which, by optimizing the available amount of spoils, makes possible a rehabilitation adapted to the morphology and dynamics of the environment. Function $f(y)$, (thick line) represents the original profile of the slope (before exploitation) and is of $a/(b+y^c)$ type; function $g(y)$, (dotted line) represents the profile to be obtained as a result of restoration, and is of the same type as $f(y)$; 1–10, control points for the geometrical design and calculation of volumes (based on areas and using integral calculations or polygonization of the curves in segments of known gradient); A_1, the volume of material, which it is estimated will be mobilised in the short term from the abandoned quarry face through natural dropping, and which makes it possible to calculate the dimensions of the trench at the scarp foot (A_2); $A_2+A_3+A_4$, the volume of material extracted during the exploitation of the quarry; A_5, the volume of spoils produced during exploitation; A_6, the volume of material from the original slope which must be mobilised, together with the spoils (A_5), in order to reconstruct unit A_4; A_4, the volume which must be filled in order to reconstruct, together with A_2, profile $g(y)$, so that $A_2+A_4=A_1+A_5+A_6$; A_2, the volume of material which cannot be recovered for rehabilitation. The design is based on the assumption that, in the very long term, the versant will eventually adopt a profile subparallel to $f(y)$ through retrocession of the top of the slope.

Table 2
Physical and chemical attributes of the materials analyzed: OS, a catena of current soils from the original slope developed on colluvial matter, samples of which were taken in areas not affected by exploitation (1–6, arrangement in the catena, 1 top, 6 bottom); CO, surface deposits (colluvium) mixed with the spoils; SP, sand spoils

	Physical analysis				Chemical analysis								
	%					%				mg/100 g			
	Sand	Silt	Clay	Texture	pH	N	Organic matter	C	CO_3^{2-}	P_2O_5	K^+	Ca^{2+}	Mg^{2+}
OS-1	27	55	18	Silt loam	7.54	0.138	3.54	2.06	16.0	4.5	14	215	22.5
OS-2	33	50	17	Loam	7.86	0.146	3.74	2.17	16.4	4.5	10.5	300	19.0
OS-3	43	45	12	Loam	7.70	0.244	6.63	3.85	15.8	7.0	10	216	17.8
OS-4	58	26	16	Sandy loam	7.79	0.086	2.28	1.32	17.5	6.5	7	386	20.8
OS-5	61	27	12	Sandy loam	7.74	0.252	5.44	3.16	16.2	17.0	20	276	19.5
OS-6	45	40	15	Loam	7.69	0.131	3.74	2.17	18.3	76.0	12	117	17.0
CO-a	33	42	25	Loam	8.00	0.012	0.41	0.24	21.0	11.0	6	235	34.3
CO-b	41	35	24	Loam	7.98	0.015	0.54	0.32	23.4	9.5	5	250	26.5
CO-c	66	20	14	Sandy loam	8.00	0.011	0.44	0.26	12.1	9.0	4	168	13.3
SP-a	89	6	5	Sand	7.03	0.008	0.20	0.16	1.1	<1	2	30	3.5
SP-b	90	3	7	Sand	7.18	0	0.25	0.14	0	<1	2	12	3.0
SP-c	92	5	3	Sand	7.05	0	0.27	0.16	0	<1	2	16	3.1

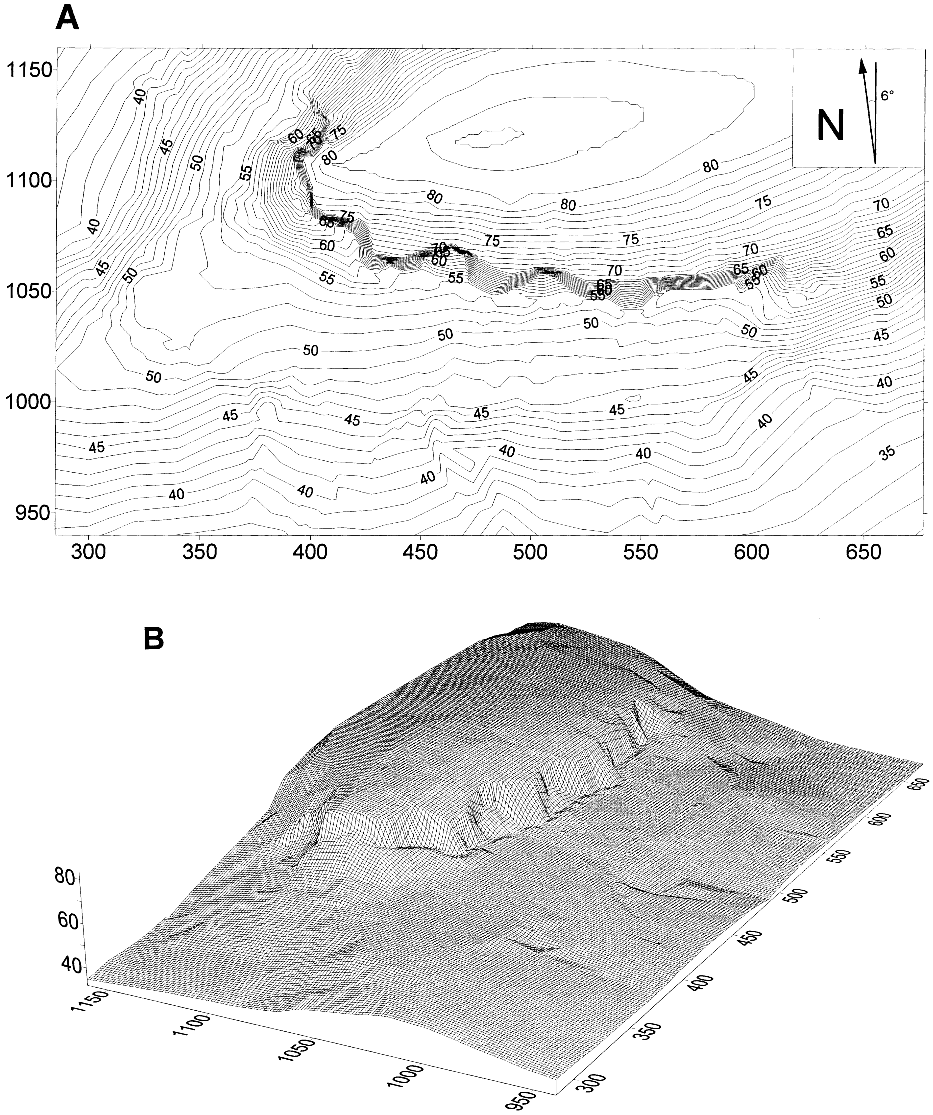

Fig. 6. Projected situation following rehabilitation. A: final contour map. B: block diagram seen from the SW (SURFER 5.1 program). Distances in metres.

Based on the texture of the material and on the morphological design, the rehabilitation plan envisaged the arrangement of the coarser material in the lower areas and of the finer material on the higher levels imitating the granulometric seriation of a weathering profile. This structure would allow higher water retention at the higher levels and slow infiltration to the lower levels, with subsequent accumulation of water at the lower areas saturated layers were forming in the manner of a natural aquifer. At the same time, this arrangement would increase geotechnical stability.

The texture of the former colluvia (mixed with the spoils) was mainly loamy, and to a lesser degree loamy/sandy. Their pH was uniform (around 8), a value which does not affect the availability of nutrients (Aguiló, 1992). The organic matter content could be considered to be deficient. The nutrient content, on the

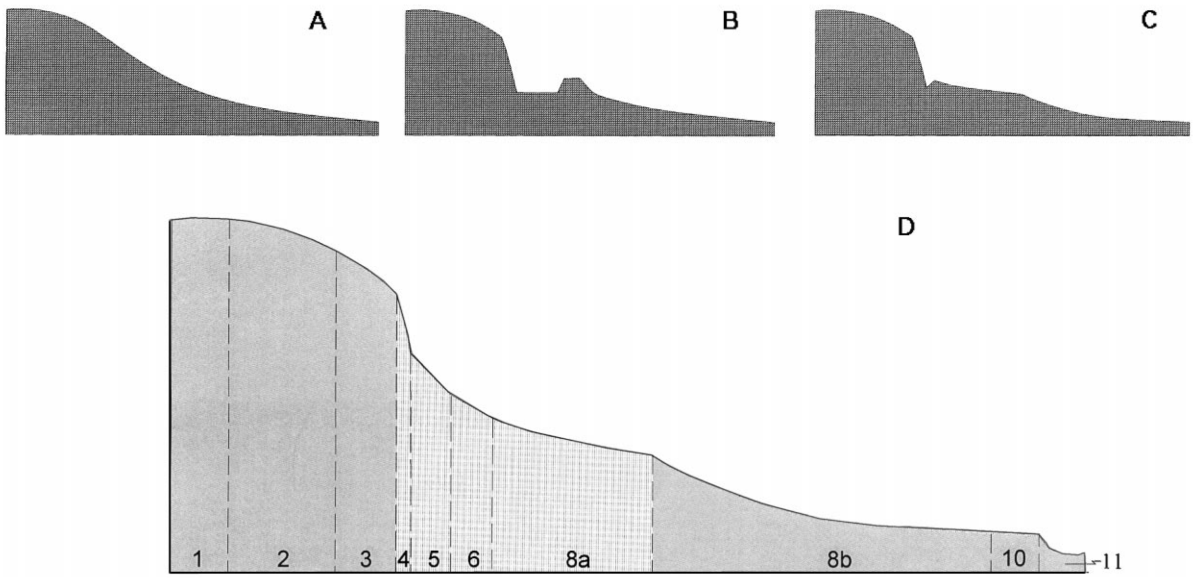

Fig. 7. Morphological evolution of the hillside. A: profile of the original slope. B: model profile of the abandoned quarry. C: profile following rehabilitation. D: resulting profile with geomorphological evolution in the short or medium term (based on landsurface model of Dalrymple et al., 1968); in the long or very long term, it is assumed that the slope will adopt a profile subparallel to A. 1–11, geomorphological units mapped in Fig. 3; 1, 2, 3, 8b, 10 and 11, remains of the original slope; 4, 5, 6 and 8a, rehabilitated surface.

other hand, was so low that the material was classified as deficient in essential nutrients (nitrogen, phosphorus and potassium).

In view of these results, it was decided that the considerable amounts of colluvial material scattered among the spoils was appropriate for the development of the future soil. There were several reasons for this (Bradshaw and Chadwick, 1980; Nichols et al., 1985; López, 1989): (a) this material formed the substratum, on which the original soils on the slope had developed prior to the extraction activity; (b) the nature of the substratum which remained as a result of the mining activity (silica sands and clays) would, in any rehabilitation plan, need to be amended with materials of carbonate composition in order to raise the pH level to neutral (or, in this case, even to modify it to slightly basic); (c) its loamy texture made it ideal for edaphic development; (d) it contained remains of the original seed bank of the soil; (e) it contained, although in small proportions, certain amounts of principal nutrients and organic matter.

Clearly, however, these results also showed that, chemical fertilisers needed to be added to this edaphic substratum in order to trigger a new process designed to develop a vegetation cover. Specifically, it was considered necessary to use an NPK complex (12/36/12) fertiliser, using a proportion of 600 kg/ha. In addition, due to the low proportion of nitrogen, it was necessary to use species which fix nitrogen in the revegetation process (legumes). Used together with gramineae, these would promote the rapid establishment of a vegetation cover, capable of rapidly generating organic matter which could be incorporated into the soil, thus, facilitating the development of horizons with humus as the first step towards edaphic and vegetative development.

The final selection of the species to be used in the revegetation process was determined by environmental factors and the objective of the reclamation. The selection was made with the advice of specialists and the mixture selected was: 30% *Onobrichis sativa*; 30% *Medicago sativa*; 10% *Lolium multiflorum*; 15% *Agropyrum desertorum*; 10% *Lolium rigidum*; 5% *Veza villosa*, using a proportion of 330 kg/ha.

5. Ecological and landscape assessment of the rehabilitation

In any reclamation, it is necessary to establish a monitoring and control plan. Such a plan is even more

Fig. 8. Aerial view of the rehabilitated surface (May 1996). Photo: Paisajes Españoles S.A.

Fig. 9. The project was performed between January and February 1995. The picture shows the works relating to reconstruction of the glacis type morphology, and extending of the colluvial material on the final surface. Since the use of heavy machinery led to compactation of the terrain, decompactation work was subsequently carried out using the traditional farming techniques of the region (ripping, ploughing).

necessary in this case, since, much of the rehabilitation is left to the actions (geomorphological processes) of the very natural dynamics, it is intended to restore; the process in question is, to a considerable extent, one of 'self-restoration' (natural regeneration).

For the design of this monitoring and control plan we chose the method developed by the Batelle-Columbus (1972), which is based on evaluation of the changes occurring in time in certain features of the system (ecological indicators). Our work comprised three main stages:

1. Prior to the mining activity, the area in which the quarry was located was considerably degraded, mainly due to historical grazing and forestry activities. There were significant phenomena of degradation of the soil and of the original vegetation cover, evidenced by the existence of significant erosion in gullies, as could be ascertained by studying aerial photographs taken in 1946 and 1956.
2. Following the abandonment of the quarry, the environmental disturbances were considerable with modifications of the relief and landscape. The vegetation and edaphic cover disappeared and significant erosion processes and gravitational movements were triggered (see Section 2.2).
3. Subsequent to the rehabilitation activities, the appearance of the area is shown in Fig. 8. This situation is considered to be provisional, since, in time the terrain will acquire a dynamic equilibrium profile based on the evolution of the scarp (see Fig. 7(D)). At the same time, a vegetation colonization will occur which will eventually lead to the restoration of a wood with similar features to those of the surrounding area. The average time estimated for completion of this process is around 50 years; this assumption is based on a study of the behaviour of the adjacent slopes.

In view of this long-term reclamation approach, it is too early to provide final results. For example, we do not know how long it will take the nitrogen and organic matter soil contents to increase to an acceptable level, and, accordingly, the project includes periodical monitoring with the related edaphic analysis. At the present time, more than 2 years after execution of the rehabilitation work (Fig. 9), we can provide some first findings obtained in the field tests

Fig. 10. Different details of the rehabilitated surface (May 1997) and comparison with the situation prior to restoration. The conditions established have enabled a satisfactory development of the vegetation cover at the slope base.

(visual assessment of the site morphology, quantification of the micromorphology of the abandoned quarry face with detailed topography, analysis of the degree of vegetation cover, general prospecting of biomass, or affinity of the various species with the substratum). Rill and gully erosion processes have been minimal at the slope foot (glacis); here also, the recovery of the surface vegetation has been satisfactory, since practically, all the seeded area has been covered by vegetation (Fig. 10); vegetation growth has been slow in those areas, in which it was not possible to recover with the colluvial material, consequently, causing the soil to develop on a sand substratum (only *Lolium rigidum* adapts to this type of substratum, and only in the case of plants of low stature); in accordance with the hypothesis established, the trench has already started to fill in through geomorphological evolution of the abandoned quarry face, with the formation of the debris slope.

6. Conclusion

The introduction of geomorphological criteria (morphography, morphodynamics, morphoevolution) in landscape restoration, enables these matters to be considered from a long-term viewpoint, based on the evolution of natural systems. Compared with restorations based on the standard geometrical designs giving priority to the establishment of plants, or to visual aspects, the alternative proposed here, expressly emphasizes the system's capacity for self-regeneration.

In the reclamation of abandoned mines, it is important to separate the original soil and surface deposits (colluvium and similar), normally mixed with spoils, in order to redistribute them later. These materials offer the best guarantee for producing the initial edaphic substratum, even when edaphic amendments and improvements are essential. In this case, the colluvial material has provided decisive physical (texture) and chemical (base content) features for revegetation.

In cases, such as the one described here, when environmental rehabilitation work is being carried out on a small budget, it is preferable to give priority to earth shifting in order to generate a morphology and a substratum suited to the geomorphological, hydrological, and edaphic system. This is the most appropriate alternative to ensure that the ecological recovery will be progressively established. Even so, minimum edaphic characteristics and initial revegetation must be ensured over the whole of the rehabilitated surface.

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