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Landscape analysis as a tool for surface mining design

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Abstract. Surface mining operations constitute one of the most visible and significant landscape offenders because of their geomorphologic and aesthetic effects. In recent years, the disturbance of the landscape owing to surface mining activities seems to be one of the most significant issues to deal with, as it raises serious conflicts between the public and the extractive industry. Therefore, it is necessary to adopt an environmentally friendly design for an excavation of any possible degree. Thus far, existing visual-impact assessment methodologies provide little support towards this direction as a consequence of their, mainly, qualitative character. In this paper we describe a new, more quantitative, methodological approach which is based on the measurement of topographic relief alteration caused by mining and quarrying works, and which makes use of modern mining software and geographic information systems tools. The methodology provides the means to adjust the excavation design in a way that minimizes visual impacts caused by the landform reprofiling. It can be applied in every stage of the life of a mine project. Moreover, if modified, it can also be used for the estimation of topographic relief alteration in projects within the construction sector that involve significant earthmoving works.

1 Introduction

Although mining is a temporary occupier of the land surface, mines can dramatically change the landscape, leaving, most of the time, evidence of their use (Sengupta, 1993). As Gagen (1992) characteristically mentions, the modern quarrying industry is capable of altering the natural landscape more comprehensively than any other peacetime human activity.

In the past the ignorance of the environmental consequences of surface mining was both 'legally and even morally acceptable" (Marcus, 1997). Today there is the need to deal with the problems, especially those concerning the landscape disturbance, at an early stage of the quarry design, so as to prevent intense reactions of the public against surface mining activities. So far, the primary tool towards this aim is the assessment of the visual quality of the landscape. The latter is measured by a variety of methods that evaluate the landscape character on the basis of landscape features. Several reviews of the pertinent literature are available (Arthur et al, 1977; Briggs and France, 1980; Kaplan and Kaplan, 1982; Smardon et al, 1986; Bishop and Hull, 1991; Lothian, 1999). However, expert landscape-quality assessments have been criticized for having inadequate levels of precision (Daniel and Vining, 1983). Moreover, most of the visual impact assessment methodologies are semiquantitative and conclude in terms of visual quality objectives or visual sensitivity classes (BLM, 1980; PBC, 1997; USDA, 1973) without being capable of assessing the magnitude of impact caused by mining activity. Hence, they provide little help in the context of modern environmental management.

Nowadays, surface mining design, on the grounds of landscape assessment, must meet stringent criteria of precision, reliability, and validity in order to meet biological, economic, and legal concerns (Cats-Baril and Gibson, 1986; Palmer and Hoffman, 2001). In the case of mining and quarrying activities, the potential visual impact is the result of three principal sources, namely, quarry landforms, mobile plants, and built structures (Nicholson, 1995). The reprofiling of the landform constitutes the main source of visual impact, because at the end of operations the mobile plant is transferred and all built structures are usually disassembled. Therefore, such reprofiling should have been of major concern in order to design surface mining operations on a more environmentally compatible basis. However, to do so requires that alternative pit designs are compared, in an objective way, with each other, in order to determine the design that satisfies technical and financial considerations (profitability of the project, ore recovery, etc),

A key factor in achieving better results is the development of procedures capable of quantifying the various aspects of visual impact (Bishop, 1997). As Daniel (2001) notes, it is not sufficient simply to determine which landscape condition is aesthetically better, we must also know *how much* better. Towards this aim, the present paper presents a new methodological approach for the measurement of topographic relief alteration in quantitative terms, and takes advantage of modern tools, such as contemporary mining software and geographical information system environments. The results are quite promising, since it is proved that the methodology developed is capable of providing a coherent framework for the design and the evaluation of surface mining installations.

2 Methodological approach

For the measurement of the topographic relief alteration, five indices are formed, namely the landform index (I_L), the altitude index (I_A), the adjusted landform index (I_{AL}), which is produced as a combination of I_L and I_A, the slope index (I_S), and the aspect index (I_{As}). Each one of these indices determines the average alteration of specific landform characteristics during surface mining. The degree of alteration is a linear combination of I_{AL}, I_S, and I_{As}. The necessary data for the calculation of each of the indices formed result from digital terrain models (DTMs) created for the original contour and for the shape of the excavation. The program used for this purpose is ArcView.

2.1 Landform index

I_L is a quantified measure of the association between the original contour and the final shape of the excavation. This means that the specific index examines whether the excavation follows the lines of the original contour. The development of I_L is based on spatial statistics and random-variables theory. On this basis, the properties $z(x)$ (elevation, slope, etc) of a certain point are random variables and the landform is considered to be the realization of a random function. Hence, landform is considered to be a regionalized phenomenon and each point property $z(x)$ is treated as a regionalized variable. On the grounds of the above, both the original contour and the final shape of excavation constitute two regionalized phenomena, for which the degree of their association must be found.

The variance of the difference between two random variables is defined as follows:

$$\mathrm{var}(X-Y) = \mathrm{var}(X)+\mathrm{var}(Y)-2\mathrm{cov}(X, Y) . \tag{1}$$

When the X and Y variables are correlated then the following equation is valid:

$$\mathrm{var}(X-Y) = \mathrm{var}(X) = \mathrm{var}(Y) = \mathrm{cov}(X, Y) ,$$

$$\mathrm{var}(X-Y) = \mathrm{var}(X)+\mathrm{var}(Y)-2\mathrm{var}(X) = 0 .$$

When the X and Y variables are independent, then $\mathrm{cov}(X, Y) = 0$, and consequently:

$$\mathrm{var}(X-Y) = \mathrm{var}(X)+\mathrm{var}(Y) .$$

In the case of the topographic relief, the X and Y variables represent the altitudes of the original (Z_{orig}) and the final (Z_{fin}) topography, respectively, for all the sampling points within the quarry boundaries.

In order to quantify the degree of association between the original and the final topographic relief the following equation was set:

$$I_{\mathrm{L}} = \frac{\mathrm{var}(Z_{\mathrm{orig}}) + \mathrm{var}(Z_{\mathrm{fin}}) - 2\mathrm{cov}(Z_{\mathrm{orig}}, Z_{\mathrm{fin}})}{\mathrm{var}(Z_{\mathrm{orig}}) + \mathrm{var}(Z_{\mathrm{fin}})}, \tag{2}$$

where Z_{orig} are the altitudes of the original topography, and Z_{fin} are the altitudes of the final topography. The denominator was used for the normalization of the results. In this way I_{L} ranges from 0 to 1. More specifically, when there is no relationship between the two surfaces their covariance value equals 0 and consequently I_{L} equals 1, as shown in equation (3).

$$I_{\mathrm{L}} = \frac{\mathrm{var}(Z_{\mathrm{orig}}) + \mathrm{var}(Z_{\mathrm{fin}})}{\mathrm{var}(Z_{\mathrm{orig}}) + \mathrm{var}(Z_{\mathrm{fin}})} = 1\,. \tag{3}$$

In the case in which a uniform vertical shift of the original contour takes place (figure 1), the two surfaces vary together, which means that

$$\mathrm{var}(Z_{\mathrm{orig}}) = \mathrm{var}(Z_{\mathrm{fin}}) = \mathrm{cov}(Z_{\mathrm{orig}}, Z_{\mathrm{fin}}),$$

hence,

$$I_{\mathrm{L}} = \frac{2\mathrm{var}(Z_{\mathrm{orig}}) - 2\mathrm{var}(Z_{\mathrm{orig}})}{2\mathrm{var}(Z_{\mathrm{orig}})} = 0\,. \tag{4}$$

In this case the ideal situation exists in which the exploitation has changed the topographic relief only vertically, without disturbing the continuity of the original contour.

On the basis of several quarry exploitation cases examined, I_{L} is classified into ten categories (table 1, over), where category 1 denotes the best condition and category 10 the worst.

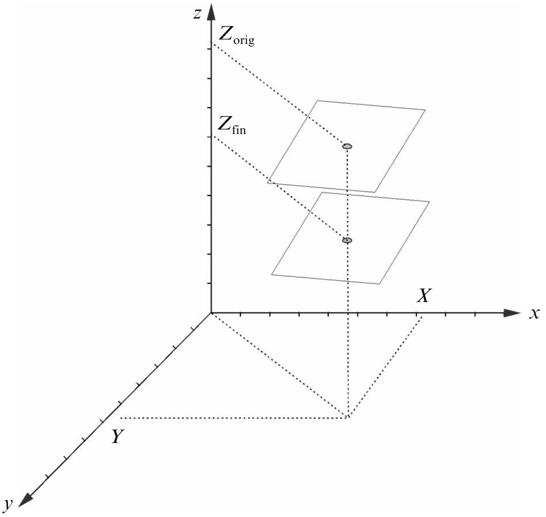


Figure 1. Alteration of a sampling cell of topographic relief owing to vertical shift.

Table 1. Classification of the landform index.

Landform index class	Values
1	0.00–0.15
2	0.16–0.25
3	0.26–0.35
4	0.36–0.45
5	0.46–0.55
6	0.56–0.65
7	0.66–0.75
8	0.76–0.85
9	0.86–0.95
10	0.96–1.00

2.2 Altitude index

Even when the excavation causes only a vertical shift of the original contour, there is still a change in the topographic relief, owing to the altitude alteration, which must be measured. For that reason I_A was set as a corrective index to I_L. The equation developed is a modified form of the standard deviation. More specifically, I_A measures the vertical change of the topographic relief on the assumption that no other change has occurred. For that reason, the mean altitude of the final surface is estimated and a new surface is created ($Z_{\text{pseudofin}}$), which differs from the original surface only in elevation, as shown in equation (5):

$$Z^i_{\text{pseudofin}} = Z^i_{\text{orig}} - \bar{Z}_{\text{fin}} , \tag{5}$$

where $\bar{Z}_{\text{fin}}$ is the mean value of Z_{fin}.

I_A measures the deviation of the sampling points of the two surfaces (original and pseudofinal relief) from the mean altitude of the original surface and is described as follows:

$$I_A = 100 \left\{ \frac{\left[\sum_{i=1}^{v} (Z_{\text{pseudofin}}\, i - \bar{Z}_{\text{orig}})^2\right]^{1/2} - \left[\sum_{i=1}^{v} (Z_{\text{orig}}\, i - \bar{Z}_{\text{orig}})^2\right]^{1/2}}{\left[\sum_{i=1}^{v} (Z_{\text{orig}}\, i - \bar{Z}_{\text{orig}})^2\right]^{1/2}} \right\}$$

$$= 100 \left\{ \frac{\left[\sum_{i=1}^{v} (Z_{\text{pseudofin}}\, i - \bar{Z}_{\text{orig}})^2\right]^{1/2}}{\left[\sum_{i=1}^{v} (Z_{\text{orig}}\, i - \bar{Z}_{\text{orig}})^2\right]^{1/2}} - 1 \right\} , \tag{6}$$

where Z^i_{orig} is the point elevation of the original terrain at X, Y coordinates, $Z^i_{\text{pseudofin}}$ is the point elevation of the pseudofinal terrain at X, Y coordinates, and $\bar{Z}_{\text{orig}}$ represents the mean altitude of the original terrain. The deduction of the arithmetic value 1 is used for the normalization of the results. I_A is also divided into ten value classes (table 2), from a study of different exploitation cases, where class 1 denotes the best condition and class 10 the worst.

2.3 Adjusted landform index

I_{AL} is a linear function of I_L and I_A. As mentioned before, I_A is a corrective index to I_L, as the change caused by the vertical shift of the surface does not disrupt the main

Table 2. Classification of the altitude index.

Altitude index class	Values (%)
1	0 – 10
2	11 – 20
3	21 – 30
4	31 – 40
5	41 – 50
6	51 – 60
7	61 – 70
8	71 – 80
9	81 – 90
10	>91

edges of the original surface. Thus, the weighting of I_A should be much lower than the weighting of I_L. The final weights of the two indices were determined after performing a sensitivity analysis using different weight combinations. The estimation of I_{AL} was then set as follows:

$$I_{AL} = 0.8\,I_L + 0.2\,I_A\,. \tag{7}$$

I_{AL} is classified into ten categories (table 3), ranging from value 0.1 to value 1.0. The value 0.1 stands for the best condition, meaning very low landform alteration, whereas value 1.0 stands for the worst condition, meaning very high landform alteration.

Table 3. Final ranking of the adjusted landform index.

Class of altitude index	Class of landform index									
	1	2	3	4	5	6	7	8	9	10
1	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.7	0.8
2	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.8
3	0.1	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9
4	0.2	0.2	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9
5	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9
6	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.8	0.9
7	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9	0.9
8	0.2	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0
9	0.3	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0
10	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.8	0.9	1.0

2.4 Slope index

I_S estimates the average slope difference between the original and the final DTM. The standardized scale of I_S ranges from 0 to 1 and is calculated, as follows:

$$I_S = \frac{1}{v}\sum_{i=1}^{v}\frac{|S^i_{\mathrm{orig}} - S^i_{\mathrm{fin}}|}{90^\circ}, \tag{8}$$

where S^i_{orig} is the slope of the original DTM at the sampling cell i and S^i_{fin} is the slope of the final DTM at the sampling cell i.

The denominator indicates the maximum inclination of a sampling cell towards the horizontal level (figure 2, over) and is used in order to normalize the results. I_S is classified into five categories (table 4, over), on the basis of the slope categories that usually occur in open pit designs, where category A denotes the best condition and category E the worst.

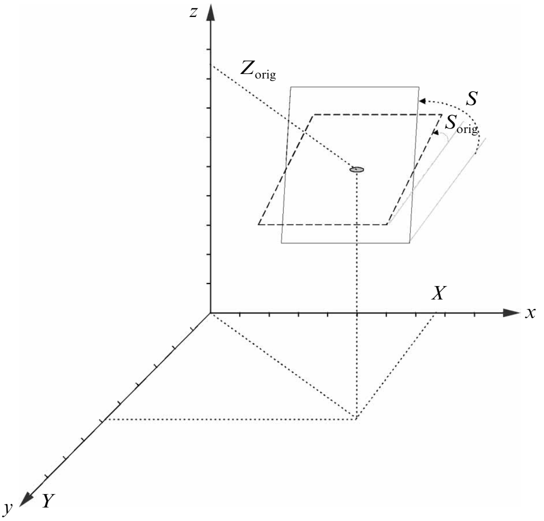


Figure 2. Alteration of a sampling cell of topographic relief owing to slope change.

Table 4. Classification of the slope index.

Slope index class	Values
A	0.00 – 0.05
B	0.06 – 0.15
C	0.16 – 0.30
D	0.31 – 0.60
E	0.61 – 1.00

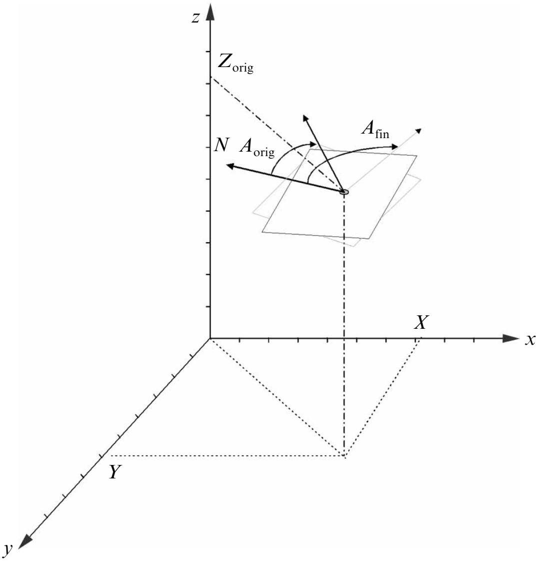


Figure 3. Alteration of a sampling cell of topographic relief owing to aspect change.

2.5 Aspect index

I_{As} measures the average aspect change between the original and the final DTM. The standardized scale of I_{As} ranges from 0 to 1 and is estimated, as follows:

$$I_{\mathrm{As}} = \frac{1}{v}\sum_{i=1}^{v}\frac{|A^{i}_{\mathrm{orig}} - A^{i}_{\mathrm{fin}}|}{180^{\circ}}, \tag{9}$$

where A^{i}_{orig} is the aspect of the original DTM at the sampling cell i and A^{i}_{fin} is the aspect of the final DTM at the sampling cell i.

The denominator indicates the maximum aspect alteration (clockwise or counter-clockwise) of a sampling cell (figure 3) and is used in order to normalize the results. I_{As}, after the study of numerous exploitation cases, is classified into four categories (table 5), where category A denotes the best condition and category D the worst.

Table 5. Classification of the aspect index.

Aspect index class	Values
A	0.00–0.25
B	0.26–0.50
C	0.51–0.75
D	0.76–1.00

Table 6. Determination of the degree of topographic relief alteration.

I_{S} class	I_{AL} class										I_{As} class
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	
A 0.00–0.05	0.08	0.12	0.15	0.18	0.22	0.25	0.28	0.32	0.35	0.38	A
	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	B
	0.25	0.28	0.32	0.35	0.38	0.42	0.45	0.48	0.52	0.55	C
	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60	0.63	D
B 0.06–0.15	0.11	0.14	0.18	0.21	0.24	0.28	0.31	0.34	0.38	0.41	A
	0.19	0.23	0.26	0.29	0.33	0.36	0.39	0.43	0.46	0.49	B
	0.28	0.31	0.34	0.38	0.41	0.44	0.48	0.51	0.54	0.58	C
	0.36	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	D
C 0.16–0.30	0.15	0.18	0.22	0.25	0.28	0.32	0.35	0.38	0.42	0.45	A
	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	B
	0.32	0.35	0.38	0.42	0.45	0.48	0.52	0.55	0.58	0.62	C
	0.40	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70	D
D 0.31–0.60	0.23	0.26	0.29	0.33	0.36	0.39	0.43	0.46	0.49	0.53	A
	0.31	0.34	0.38	0.41	0.44	0.48	0.51	0.54	0.58	0.61	B
	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.69	C
	0.48	0.51	0.54	0.58	0.61	0.64	0.68	0.71	0.74	0.78	D
E 0.61–1.00	0.34	0.38	0.41	0.44	0.48	0.51	0.54	0.58	0.61	0.64	A
	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.69	0.73	B
	0.51	0.54	0.58	0.61	0.64	0.68	0.71	0.74	0.78	0.81	C
	0.59	0.63	0.66	0.69	0.73	0.76	0.79	0.83	0.86	0.89	D

Degree of topographic relief alteration

Very low	0.08–0.15
Low	0.16–0.25
Intermediate	0.26–0.40
High	0.41–0.58
Very high	0.59–0.89

2.6 Final classification of the topographic relief alteration

The final classification of the topographic relief alteration results from the linear combination of the indices I_{AL}, I_{S}, and I_{As}, and uses equal weighting factors.

In total, five categories for the degree of change of topographic relief are formed as shown in table 6. The main advantage of the classification is that there are specific arithmetic values in each category, making the discrimination of seemingly similar alternative plans easier. In this way, the selection of the plan with the lowest landscape disturbance can be obtained.

3 Sensitivity analysis—implementation of the methodology

The above methodology has been tested in various quarry designs, including different exploitation and rehabilitation schemes. A regression analysis has also been performed which made use of the overall data produced from the surfaces, so as to investigate the significance of the developed indices. The dependent variable is in all cases the mean elevation of the final surface that is formed either by the exploitation or by the backfilling procedures ($\bar{Z}_{\mathrm{fin}}$). The new indices are used as independent variables. In all cases, the regression coefficients proved to be significant, according to the t-statistic test. It is worth noticing, in table 7, that the greater the number of independent variables, the better the determination of the model becomes.

Table 7. Coefficient of determination of the model in the selected variables.

Independent variables[a]	R^2	t-statistics
$\bar{Z}_{\mathrm{orig}}$	0.7531	352.2880
$\bar{Z}_{\mathrm{orig}}$, I_{L}	0.7834	383.5232, −75.3905
$\bar{Z}_{\mathrm{orig}}$, I_{L}, I_{S}	0.7861	386.4723, −75.5715, −22.7980
$\bar{Z}_{\mathrm{orig}}$, I_{L}, I_{S}, I_{As}	0.7895	389.2960, −73.6446, −21.4111, −25.3124
$\bar{Z}_{\mathrm{orig}}$, I_{L}, I_{S}, I_{As}, I_{A}	0.7958	394.9566, −69.1294, −22.4293, −21.5573, −35.4760

Note: I_{L} represents the landform index, I_{S} represents the slope index, I_{As} represents the aspect index, and I_{A} represents the altitude index.

Hereinafter, the results from the implementation of the methodology in two different quarries in the Attica basin, Greece, namely the 'Merenta' quarry and the 'Ammos' quarry, are presented. The Merenta quarry has been developed at the northwestern side of Merenta Hill, 2 km southeast of Markopoulo Town, near Athens City, covering an area of 63 ha (Kaliampakos and Damigos, 1998). The Ammos quarry is situated to the south slopes of Imittos Mountain, at Koropi Municipality. It is a closed-form excavation taking up an area of about 21 ha (Kaliampakos and Menegaki, 2001). In total, seven surfaces are evaluated that represent:

(a) different exploitation sizes and types;
(b) types of exploitation developed in different elevation ranges (figures 4 and 5);
(c) different rehabilitation schemes—the backfilling in the case of the Merenta quarry was intended to restore the initial topographic relief, whereas the backfilling of the Ammos quarry was intended to establish new land uses (figure 6);
(d) different phases of rehabilitation designs; to investigate different phases, different stages of the backfilling procedure of the Merenta quarry were designed. Figure 7 (over) shows the first and the second backfilling stage. As shown, the initial disposal of the backfilling materials is not performed in a systematic way. As a result, the contours formed at this stage do not follow the lines of the original contours. On the contrary, during the backfilling progress the form of the topographic relief is getting closer to the original contours.

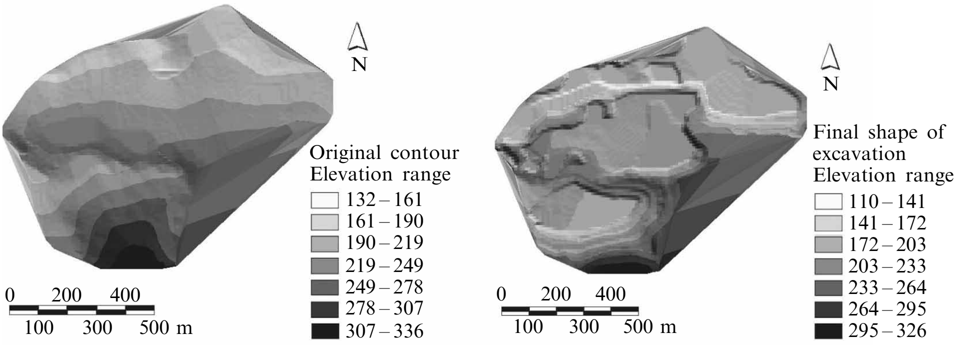


Figure 4. Digital terrain models of the original contour and the final form of the excavation of the Merenta quarry.

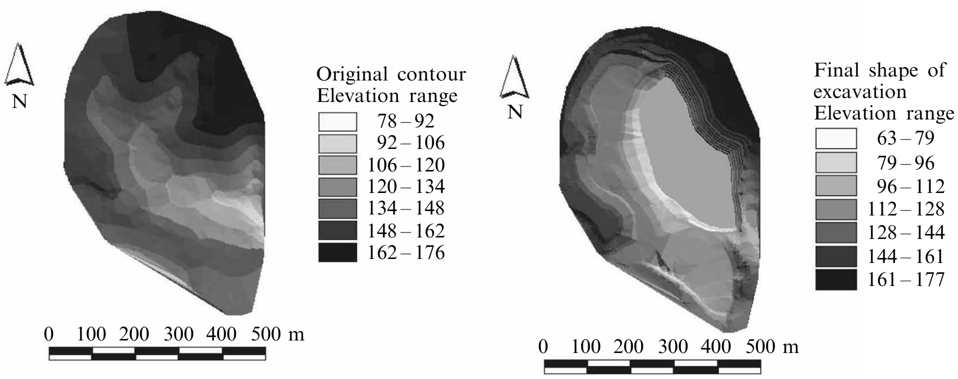
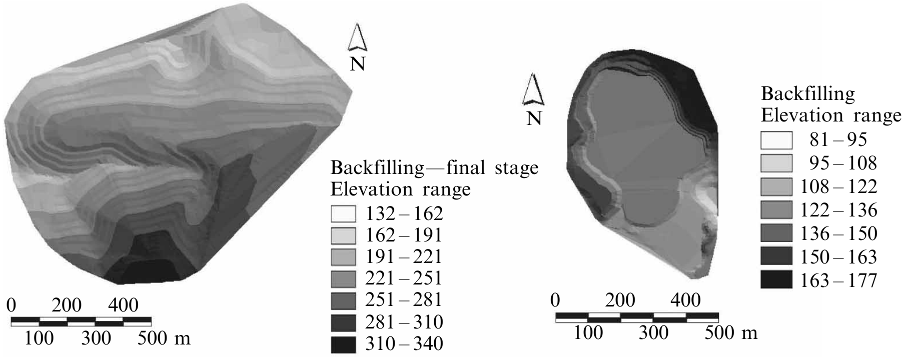


Figure 5. Digital terrain models of the original contour and the final form of the excavation of the Ammos quarry.



(a) (b)

Figure 6. The rehabilitation scheme in (a) the Merenta quarry and (b) the Ammos quarry.

As shown in table 8 (over), the degree of topographic relief alteration increases during the exploitation process and decreases during the rehabilitation process, with the exception of the first backfilling stage of the Merenta quarry, in which the degree of alteration (value 0.30) is even higher than the alteration caused by the final shape of excavation (value 0.27), owing to the unsystematic disposal of the backfilling materials.

In both cases presented, the final shape of the excavation causes an intermediate alteration. However, the two cases can be discriminated, because the alteration caused

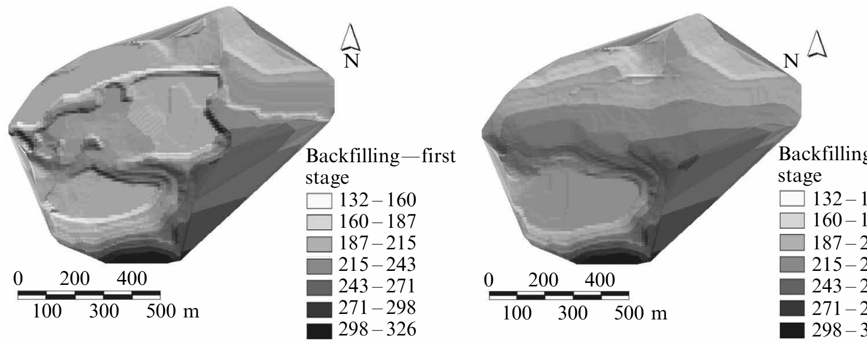


Figure 7. Digital terrain models of the backfilling stages of the Merenta quarry.

Table 8. Degree of topographic relief alteration in the surfaces under examination.

Surfaces	Indices values[a]					Degree of alteration	
	I_L	I_A	I_{AL}	I_S	I_{As}	value	class
Merenta quarry							
Final shape of excavation	0.23	0.32	0.2	0.20	0.31	0.27	intermediate
Backfilling—first stage	0.30	0.22	0.3	0.18	0.28	0.30	intermediate
Backfilling—second stage	0.23	0.04	0.2	0.11	0.17	0.15	very low–low
Backfilling—final stage	0.01	0.00	0.1	0.07	0.11	0.11	very low
Ammos quarry							
Initial excavation stage	0.32	0.43	0.3	0.16	0.36	0.30	intermediate
Final shape of excavation	0.45	0.74	0.5	0.18	0.42	0.37	intermediate
Backfilling—final stage	0.21	0.17	0.2	0.15	0.39	0.23	low

[a] I_L, landform index; I_A, altitude index; I_{AL}, adjusted landform index; I_S, slope index; I_{As}, aspect index.

by the Merenta quarry has a value of 0.27 and the alteration caused by the Ammos quarry has a value of 0.37, indicating that the Ammos quarry has a larger impact on the landscape than the Merenta quarry.

Compared with the backfilling conducted in the case of the Merenta quarry, the improvement achieved in the case of the Ammos quarry during rehabilitation is lower, owing to the different rehabilitation design selected.

4 Conclusions

On the grounds of environmental and legal concerns, surface mining and quarrying activities must take into thorough consideration the alterations caused to the landscape features. Existing visual impact assessment methods present certain drawbacks and they provide little help to engineers and decisionmakers.

The main aim of this study is to shape a coherent methodology as a tool for pit design, a methodology which involves measuring the geomorphologic alteration caused by surface mining in quantitative terms.

The methodology developed presents the following advantages:

(1) It can be used in all phases of a mining project, from the preliminary study up to mining closure, for both ex ante and ex post evaluations. Thus, it can estimate both the alteration caused by the exploitation design and the effectiveness of the proposed rehabilitation scheme.

(2) The arithmetic values given to each of the impact categories facilitate the comparative evaluation of different types of exploitation and make possible even the distinction of similar cases.

The functionality of the methodology is proven through the verification, in numerical terms, of some of the main principles in regard to the visual absorption capability of the landscape. More specifically, it is known that the ability of the landscape to absorb alteration and maintain its visual integrity is low when there is little or no variety in topography. Through the sensitivity analysis the significance of the original terrain form to the degree of change caused by the surface excavation is established. The smoother the contour lines of the initial topographic relief, the larger the alteration caused by the quarrying activity becomes (for example, the case of the Ammos quarry compared with the case of the Merenta quarry).

Moreover, it is proved, in numerical terms, that it is quite important to follow the lines of the landscape during the design of the exploitation. Thus, the excavation adopting the lines of the landscape causes a uniform shift in the initial topography relief and consequently minimizes the impact of change. Finally, given that the methodology developed has an open architecture, it can be modified to meet specific needs, so as to be used in civil works for the estimation of topographic relief alteration.

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