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Anthropogenic changes in topographic relief: applications in environmental impact assessment

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Indicators of topographic relief change are proposed for environmental monitoring, and environmental impact assessment (EIA). Changes in relief pattern reflect human impact on the land surface due to small- and large-scale development projects. Landform diversity, relief resilience and impact-response approaches allowing measurement of changes in relief pattern are described. These approaches are based on a number of integrated environmental indices that may be used together or separately to assess anthropogenic alteration of landscape elements. Several examples their practical use are given in the paper. Other possible applications of geoindicator measures for different EIA techniques are briefly described.

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INTRODUCTION

Environmental indicators are widely used for the purposes of environmental impact assessment (EIA) throughout the United States, Canada, European Union members and some other countries. The primary purpose of EIA procedure is to include a consideration of potential environmental transformation in planning, decision making and final choice of actions which maximise environmental safety (Canter, 1996).

In terms of EIA approach an environmental indicator is a parameter (measured or observed) or some value derived from parameters, which provides significant information about patterns or trends (changes) in the state of the environment or about the relationships between such characteristics (The United States Environmental Protection Agency, 1995). Traditionally environmental indicators are related mainly to ecosystems, biodiversity, biophysical and socioeconomic systems (Hunsaker and Carpenter, 1990), and relatively few deal with geological and geomorphological processes and features. At the same time geological and geomorphological environments are the basic abiotic systems which determine the soil and landscape mosaic, influence socioeconomic systems and condition the behaviour of pollutants. Therefore many types of projects which are subject to EIA procedure could have considerable impact on geological and geomorphological environments, and there is an obvious need to elaborate a number of geological (geomorphological) indicators or geoindicators for the purposes of environmental monitoring, reporting and decision making. In order to fill this gap in the state-of-the-environment (SOE) reporting a set of geoindicators has been proposed by the Cogeoenvironment working group (Berger and Iams, 1996; Berger, 1997). The geoindicators included in the set represent measures of definite geological and geomorphological processes occurring near the Earth's surface and reflect environmental changes over periods of 100 years or less. Some other attempts to include geomorphological and geological processes in assessment of rapid environmental changes have been recently made (Panizza, 1995).

Commonly the implementation of medium- and large-scale projects entail multiple impacts on the geological environment which may cause significant changes in a number of geological (geomorphological) processes and phenomena within a vast area. In this case the problem of simplification and quantitative expression of a large quantity of environmental changes arises. For example, regional development projects affect almost all the abiotic elements of landscape, changing their initial state. In order to reflect the multitude of environmental changes some

Fig. 1. Location map of the study area

Vertical line — Figs. 2, 3; oblique line — Fig. 4

complex integrated geoindicator (combining as many as possible particular geoindicators) should be derived. The multiple human impacts on the landscape abiotic elements and processes may result in topographic relief change. Thus the pattern of change may be referred to as a complex geoindicator of rapid environmental change due to human impact.

GEOINDICATOR DEFINITION

The relief pattern within a territory can be defined as a certain spatial arrangement of landforms belonging to different geomorphological types and subtypes and their constituent rocks and deposits. The relief pattern is the main abiotic base for the natural landscape mosaic. Temporal change in the spatial arrangement of landforms, including relief morphology, is a cumulative result of natural processes and the intensity, duration and trends of human impact.

A relief pattern change geoindicator possesses the following characteristics that are important for EIA purposes: (1) it addresses abiotic elements and processes of the landscape and represents their qualitative and quantitative features, (2) it combines measurements of factors or relationships assuming that these measurements are indicative of landscape changes in space and time, (3) it is based on corresponding environmental indices that are quantitative descriptions of environmental data, derived and simplified so as to be useful for decision makers, officials and public.

A relief pattern change geoindicator may be closely related to other aggregated environmental indicators frequently used in EIA procedures: landscape pattern and land use change (Hunsaker and Carpenter, 1990).

METHODS OF MEASUREMENT

Several approaches may be used to measure relief pattern change. All are based on the derivation of environmental indices that are a numerical expression of a large quantity of geological and geomorphological data.

The landform diversity approach implies measurement of landform type and subtype abundance within a certain area and landform abundance within particular types. For this purpose, indices designed to assess biological species diversity may be adapted. The simplest of these are the species deficit and Margalef indices (Chapman, 1992).

Species deficit index:

$$D = (A_1 - A_x)/A_1 x10 \qquad [1]$$

where: A_1 — number of species (landform types) in a control area; A_x — number of species (landform types) in the area of interest.

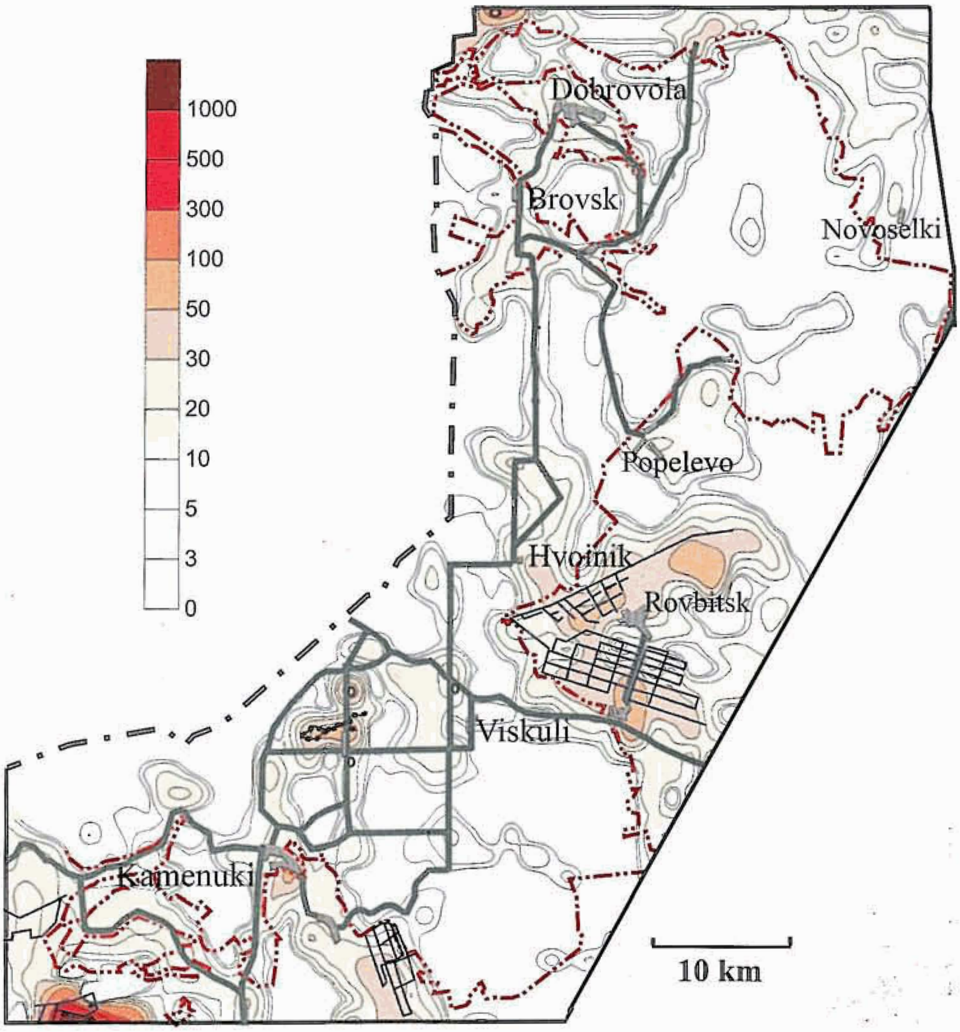
Margalef index:

$$D = (S - 1)/\ln N \qquad [2]$$

where: S — number of species (landform types) within the area of interest; N — number of individuals (landforms) within the area of interest.

The species (landform types) deficit index shows the relative diversity of landform types within the area of interest in comparison with the larger area. The Margalef index shows the relative abundance of landforms belonging to different landform types within the area of interest. These two measures (together with other more complicated diversity indices) may be applied to single out the areas that are characterised by the highest relief diversity, in order to target human impact mitigation and environmental protection in these areas. Repeated measurements will provide information on the rate and possible causes of decrease in relief and landscape diversity. Relief diversity indices may be used to estimate the aesthetic value of landscape and to carry out cost-benefit analysis assessing the consequences of industrial, agricultural and recreational actions.

The relief resilience approach entails an assessment of the capacity of a geomorphological system to absorb anthropogenic transformation without critical alteration. The approach is based on the three following environmental indices which may be used together or separately depending on the purpose of a study.



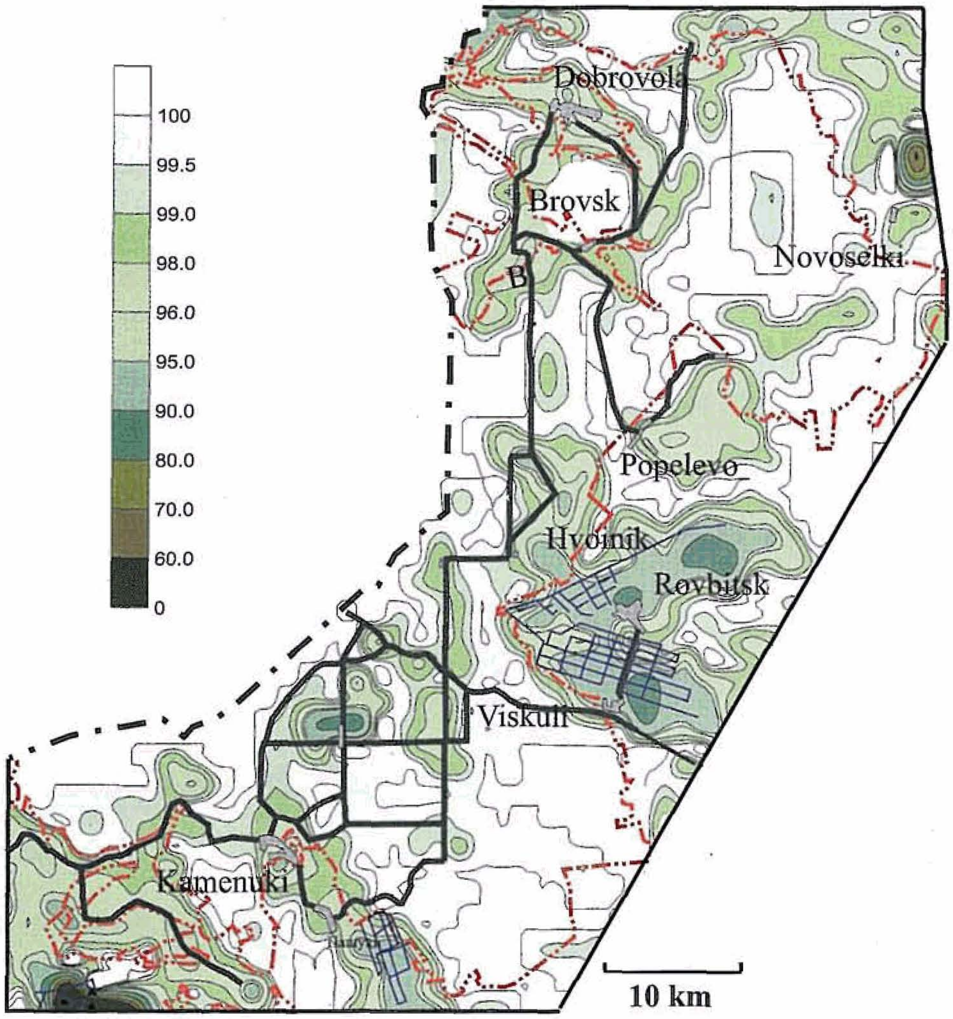
Man-induced transformation of relief (Ct) thousands m^3/km^2

Fig. 2. Anthropogenic transformation of natural relief in the Belovezskaya Puscha

The index of relief technogenic transformation (*Ct*) represents the cumulative measure of the multitude of human impacts on relief. It is equal to the sum of volumes of all man-made landforms per unit area (Savchik, 1993*a*). The *Ct* index is similar to more complicated measures that are used in anthropogenic geomorphology: the geotechnical (Brylev, 1982) and anthropogenic effect (Zapletal, 1983) indices, as well as to some cumulative measures of human influence on the land surface which are used in the state-of-the-environment reporting and EIA procedures: the surface impermeability index (Leopold, 1968; Lundren, 1986) and the watershed development index (Dune and Leopold, 1978).

Particular values of the *Ct* index can be easily calculated using data on technogenic landform parameters. These data are available from detailed topographic and geomorphological maps, aerial photographs and field studies.

The index of relief potential vulnerability (*Vn*) is a quantitative expression of the potential ability of a natural geomorphological system to absorb external transformation. In general, the vulnerability of complicated environmental systems with respect to external impact decreases as their complexity (amount of system elements and internal interactions between them) increases (Bennet and Chorley, 1978). In this sense, the volume of natural relief within some area may be chosen as an expression of the geomorphological complexity. Thus, the *Vn* index is simply the volume of natural relief calculated from the level of the first order base erosion surface. This surface is chosen because it is referred to as the base which the natural relief can be eroded by natural processes under stable climatic and tectonic conditions. Relatively high values of the total volume of natural landforms in Belarus are associated with diverse, dissected and hilly geomorphological systems with a number of high-energy geomorphological processes,



The relief resilience index (R) %

Fig. 3. The residual resilience of natural relief with respect to human alteration in the Belovezskaya Puscha

while low values of relief volume correspond to flat non-dissected areas and slow geomorphological processes.

In Belarus the most vulnerable geomorphological systems with respect to potential human alteration occur within alluvial, lacustrine and outwash plains and lowlands. Even moderate anthropogenic impact on the land surface in these areas may lead to significant changes in geomorphological processes, relief and landscape mosaic. The natural relief within end moraine and glaciofluvial upland areas is less vulnerable.

The relief resilience index (*R*) represents a cumulative measurement of the residual resilience of an existing transformed or non-transformed geomorphological system with respect to human impact. This index is based on the environmental indices *Ct* and *Vn* (see above). It is calculated using the following formula:

$$R = 100 - (Ct/Vn \times 2)\ \% \qquad [3]$$

A *Ct*/*Vn* percentage ratio of 50% is considered as a critical level of external disturbance. Values of residual resilience may range from 0 to 100%. An *R* value of 100% characterises natural non-transformed relief, and an *R* value of 0% characterises a totally artificial geomorphological system.

All these three indices may be integrated in to state-of-the-environment reporting and EIA procedures. In particular they

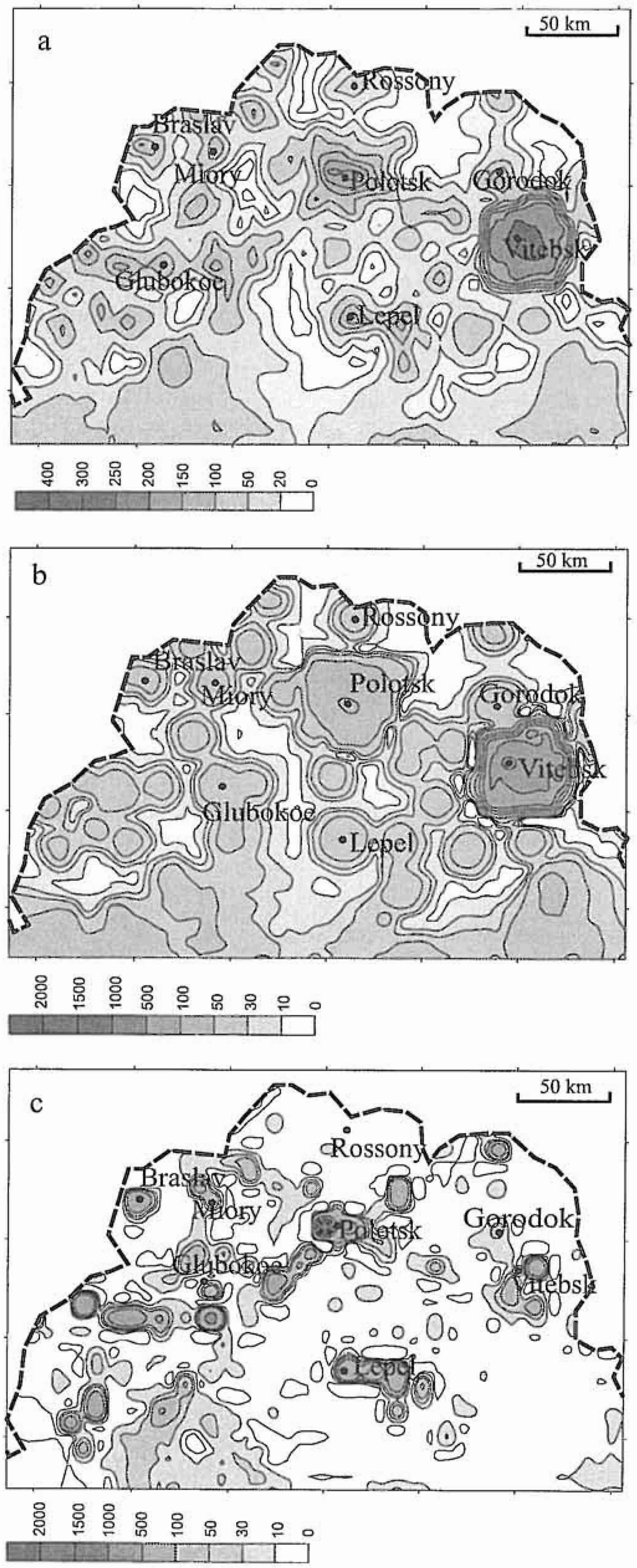


Fig. 4. Spatial distribution of predicted values of the volume of quarries in northern Belarus

Distribution of predicted values of volume (thousand m^3/km^2): **a** — of sand quarries, **b** — of clay quarries, **c** — of gravel quarries

can be easily used to determine areas with non-transformed and highly transformed relief, as well as to identify areas with potentially resistant or vulnerable relief. This approach may also be applied to assess possible changes in relief transformation and resilience due to human effects. The *Ct*, *Vn* and *R* parameters may be represented in the form of electronic databases and maps on different scales. For example, these indices were used to report the state of the environment in the Belovezskaya Puscha (Fig. 1), and elsewhere in Belarus (Savchik, 1993*a*, *b*).

The natural relief within the Belovezskaya Puscha belongs to three major genetic types: end moraine highlands (relatively small areas in the southern and northeastern part of the park); glaciofluvial areas and glaciolacustrine lowlands. Therefore, most of this area represents is relatively vulnerable as regards the external alteration of geomorphological systems. The character of human impact on the relief in the Belovezskaya Puscha differs significantly from that in adjacent areas. Civilian construction, quarrying and some other economic activities have been developed here for the purposes of recreation and forestry while agricultural and industrial activities and urbanisation have been hindered for centuries.

The spatial distribution of the relief technogenic transformation index over the area studied is given in Figure 2. The average *Ct* value is 9.7 thousand m^3/km^2 within the park borders, and 14.8 thousand m^3/km^2 in the adjacent area, which is lower then the average *Ct* for the whole country (27.8 thousand m^3/km^2). Hence there is a relatively low intensity of human impact on the relief in the Belovezskaya Puscha. At the same time some areas may be referred to as spots of highly transformed relief. The *Ct* values in the southwestern corner of the studied area exceed 1 million m^3/km^2 which is connected with the large peat mining fields. Although this altered territory is situated out of the natural reserve, it significantly influences the National Park ecosystems through the emission of dust, pollution of water and general destabilisation of soil water regime. Relatively high *Ct* values are registered within the Belovezskaya Puscha (50–100 thousand m^3/km^2). They coincide with quarries, dams, roads and other artificial landforms that transform the landscape. Almost 50% of the park territory represents virgin non-transformed geomorphological systems. These areas are expected to be refuges of unique undisturbed landscapes and ecosystems that possess a great value in Europe. Repeated mapping of the *Ct* index enabled recognition of spots of increasing anthropogenic pressure and guided measures aimed at the mitigation of human impact. Thus a slight increase in *Ct* values (15–20%) has occurred in the southern and central part of the National Park since 1994, due to development of the transport infrastructure and construction for the purposes of recreation.

The spatial distribution of the *R* index over the Belovezskaya Puscha territory (Fig. 3) shows that almost 70% of the area studied possesses very high values of the *R* index (99–100%), and only 5% of the park territory may be referred to as the areas of environmental concern (*R* from 80 to 60%). The lowest *R* values (less than 20%) are distributed out of the park borders and coincide with peat fields. Repeated calculations and mapping of the relief resilience index show a slight increase in values since 1994 in the central part of the park. This information was used by the park administration to propose measures targeting human impact mitigation in the areas of concern.

The impact-response approach describes how a dependent parameter varies when influenced by a set of independent parameters. The independent and dependent variables may represent both the human impacts and natural "response processes". The importance of such models consists in the numerical representation of intra-system relationships, which can then be used to make short- and long-term predictions of impact consequences.

The simplest example of an impact-response model is statistical regression analysis. Such an analysis was used to determine the range of socioeconomic and natural factors which influence the intensity of quarrying of building materials in areas of the Belarus Poozerie region, north of the maximum limit of the last Pleistocene glaciation. Analysis of the possible relationships between the volume of sand, clay and gravel quarries and a number of independent variables showed that natural factors (geological and geomorphological features) do not influence significantly variation in the dependent parameters. The high diversity of landforms and easy availability of sand, clay and gravel deposits may explain this. Among the variables influencing variation in the dependent parameters are several socioeconomic factors such as the density of roads, the distance to the nearest town (city) and the number of inhabitants in the nearest town (city). The following two equations of multiple linear regression and one equation of exponential regression describe the relationships between variables in the process of quarrying sand, clay and gravel correspondingly:

$$Y_1 = 89.71 + 195.9X_1 - 6.46X_2 + 0.72X_3 \quad [4]$$
$$n = 101, R = 0.68$$

$$Y_2 = 347.3 - 25.29X_2 + 6.87X_3 \quad [5]$$
$$n = 18, R = 0.81$$

$$Y_3 = 0.11e^{(10.1X_1)} \quad [6]$$
$$n = 46, R = 0.67$$

where: Y_1, Y_2, Y_3 — volumes of sand, clay and gravel quarries in thousands of cubic metres per square kilometre; X_1 — density of roads in km/km^2; X_2 — distance to the nearest town (city); X_3 — amount of inhabitants in the nearest town (city) in thousands; n — excerpt value; R — correlation coefficient.

Then, the models derived were used to compose maps of predicted values of the volume of sand, clay and gravel quarrying over northern Belarus (Fig. 4). The predicted values of the volume of sand quarries, calculated using the model [4] increase on approaching large settlements and main highways (Fig. 4a). The volume of clay quarries increase as approaching the towns, in proportion to the population of these towns. Therefore isolines of Y_2 values surround the towns (Fig. 4b). The density of isolines representing the volume of gravel quarries increase on approaching the main transportation corridors Vitebsk–Polotsk–Riga and St. Petersburg–Polotsk–Minsk (Fig. 4c).

These maps give useful information for SOE reporting. Both the statistical equations and maps of predicted values are also helpful in assessing the probability of elimination of different landforms which are a source of building materials. It is very likely that landforms composed of high quality sand, gravel and clay in the areas where predicted values of Y_1, Y_2 and Y_3 are high will be eliminated by mining and construction activities. Thus, predictive maps may serve as a tool for environmental planning and decision making. The impact-response approach may also be used in EIA procedures while assessing possible environmental impacts of development projects which entail different socioeconomic changes (in our case population growth, appearance of new populated sites and an increase in the density of roads). A similar approach was used to assess the environmental impact of aggregate mining in Malaysia, where rapid economic growth caused an increase in aggregate consumption and extraction which resulted in multiple environmental changes (Pereira and Ng, 1999).

CONCLUSIONS

Relief pattern change reflects the character and intensity of natural geomorphological and geological processes of both long and short time duration. Alternations to the pattern of relief pattern change gives information on the quality and intensity of human impact on the physical substratum. Current trends in relief pattern change can be used to predict the future landscape, trends and intensity of geomorphological processes and deleterious changes in social and economic spheres. This indicator can also be used to reconstruct the character of Earth processes, the landscape pattern and human impacts on the past physical landscape.

The proposed indices quantitatively describe multiple changes in the relief pattern, and in this sense they are similar to other cumulative measures which have been used for decades in EIA and SOE reporting. Thus, well-known environmental-media indices of air and water quality are derived to combine many environmental variables into one single value (Ott, 1978; Canter *et al.*, 1987). Therefore all the approaches and indices introduced to summarise and interpret changes in the relief pattern are easy to integrate in EIA techniques.

They can be used in simple methods of impact identification, to describe affected environments, in selection of proposed actions and in study summarisation. For example, they may be included in simple interaction matrixes (Leopold *et al.*, 1971), stepped cross-impact matrixes, networks and checklists (Canter, 1986). Also the relief pattern change measures may serve as an important tool for comprehensive prediction and assessment of environmental impacts of actions related to construction, land-use change, minerals extraction (either mining or quarrying), waste disposal, and so on.

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