

The concept of multi-criteria mineral resources protection

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Abstract The author deals with a complex, multi-criteria system of protection of mineral resources, based on the evaluation of their deposits, both with identified and inferred reserves, and perspective areas, i.e., the areas where mineral deposits may occur. The purpose of valorization is to compare different deposits using the same, uniform criteria, and then assign them to particular groups with the intention of protecting the most valuable deposits and highly perspective areas more efficiently. The criteria represent three separate groups: geological and mining assets, the level of certainty (the degree of our knowledge on the mineral raw material and its deposit), as well as environmental and spatial planning constraints. Inclusion of the prognostic areas (the D_1 category of resources in Poland) to the procedure of deposit valorization forms the basis for their legal protection, especially when they have not been protected until now.

Keywords Protection of mineral resources · Mineral deposits · Perspective areas · Multi-criteria evaluation

Introduction

Dynamic growth of urbanization and nature protection areas causes numerous conflicts between mining and spatial planning. The presented paper describes the concept of multi-criteria evaluation of mineral deposits

and perspective areas of their existence aimed at protecting mineral resources. The latter is understood as the protection of the area where a given deposit does occur or may occur, from such proposals of land use planning that might exclude or hinder future exploitation of the deposit. They mainly include permanent infrastructure investments (roads, railways, water intakes and their adjacent zones, etc.), industrial and housing development as well as restrictive forms of nature protection.

Mineral resources should be protected mainly with regard to their non-renewable character and uneven spatial distribution. This refers to identified reserves of mineral commodities, in particularly undeveloped or abandoned mineral deposits, those present in currently explored areas, as well as reconnaissance resources that may occur in perspective (resource favourable) areas. Such areas sometimes comprise vast terrains under different land use, and the idea of protecting them may jeopardize a long-term industrial, housing or infrastructure development, collide with plans of the local administration and the short-term interests of local inhabitants. This is a source of conflict that may be settled only by finding solutions with regard to the priorities of spatial planning. In order to achieve an expected compromise, the evaluation of mineral deposits has to provide a basis for protecting the most valuable deposits at the expense of less valuable ones, i.e., those that are smaller and/or contain mineral commodities of an inferior quality.

A similar approach should be followed when evaluating perspective areas (areas of possible occurrence of deposits). The reconnaissance resources represent a potential that could secure the future domestic needs for mineral commodities. Protection of the most

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valuable resources is very important in the context of sustainable development for of a country.

Problems related to the protection of natural raw material resources have been perceived, understood and probably structured in the best way in the USA. The idea of the resource protection came into being in America at the beginning of the twentieth century, through the pioneering work of Van Hise. The crucial matter was to secure appropriate reserves of mineral commodities for the country, taking into account that the non-renewable resources shown are permanently decreasing and their future shortage is inevitable. Thus, the important task was to define activities allowing utilization of the mineral deposits for as long as possible. Following the initial phrasing, the idea of the deposit protection referred to a reduction of mining and processing losses, economic use of mineral raw materials, and the common introduction of recycling and substitution (Van Hise 1922).

In Poland, a similar approach was introduced by Walery Goetel in 1960s. He made the ground-breaking contribution with his concept of “sozology”: a Polish term for all activities aimed at conserving and protecting the biosphere from the destructive effects of anthropopression (Goetel 1966).

This first, classical approach has to be broadened today with a request to ensure access to explored and reconnaissance resources, through making available the areas where they occur, i.e. protecting these areas from development and saturation with permanent infrastructure, buildings and other facilities.

The protection of the reserves in the deposits under ongoing exploitation is controlled, to a higher or lower degree, by a proper feasibility study and executed in most countries through an adequate concession policy. The task of protecting the deposit-rich areas is tackled very diversely: from legal protection of all known (although unexploited) mineral deposits (e.g., the Czech Republic—Reznicek 1987) to the complete absence of regulations (e.g. Finland or Portugal—Podemski 2002). General remarks concerning the protection of deposits are expressed in the opinion of the European Commission, which points to the importance of accessibility to the areas rich in mineral raw materials, as a crucial element in a competitive mining industry (Commission of the European Communities 2000; Berlin II 2002). The most straightforward recommendations, supported by detailed exploitation regulations within the framework of sustainable management, have been formulated in Great Britain. There they have introduced an order delimiting the so-called mineral commodity consulting areas, in which investment is strictly controlled. These areas must be taken into account when preparing any

planning documents (management plans). Such plans stipulate that a mineral commodity must be exploited prior to any other forms of a permanent surface investment. Legal regulations of the Great Britain show many similarities to those in the USA, where one of the tasks of the state geological surveys is to evaluate the presence of deposits and perspective areas for the purpose of spatial planning and further discussions on future landscape management. With similar meaning in Germany, we have the “Raw material protection areas” (Rohstoffsicherungsgebiete) which are included within all regional plans.

Materials and methods

This paper presents the proposal for a complex evaluation of rock and ceramic mineral raw materials (such as ceramic clays, crushed and dimension stones, sands and gravels, etc.), contained both in the known deposits and their perspective areas that is based on three groups of criteria:

- natural geological and mining assets,
- environmental and spatial planning constraints,
- the level of certainty (i.e. the degree of our knowledge on the resources in question).

The idea of the evaluation is shown in Fig. 1. The geological and mining assets of the deposit and of the mineral commodity are the most important in the evaluation. The environmental and spatial planning constraints (the second group of criteria) point to possible difficulties in the development of the deposit and further mining activities. Resulting from formal, legal decisions, these constraints may be a subject to discussions, modifications and changes. Therefore, they are less important in the evaluation.

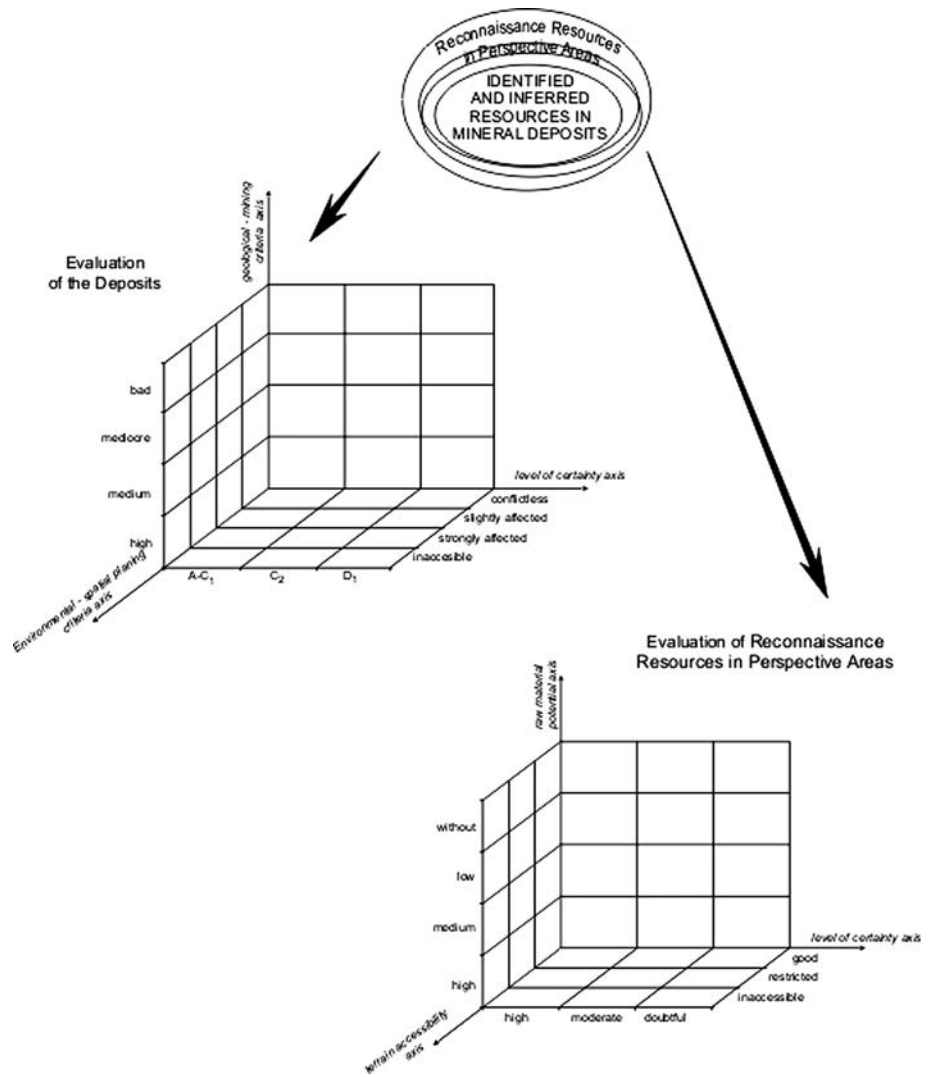
In addition to the two distinguished groups of criteria, one more element, i.e., a level of certainty of information provided and analysed in the geological study on the deposit, has to be considered during the assessment procedure. This level defines the state of recognition of resources and the risk of their erroneous evaluation, as well as outlining the range of further exploratory works necessary for a reliable assessment of the deposit assets.

Evaluation of mineral deposits

Criteria associated with the character of the mineral commodity and of its deposit

The valuation of geological and mining assets of a particular deposit depends on several parameters.

Fig. 1 Model of resource valorization in mineral deposits and in the perspective areas



These are: the quality and variability of the mineral commodity, the range of its possible usage, substitution possibilities, frequency distribution of the commodity occurrences, deposit size (volume of identified resources), geological and mining conditions, and variability of the main geological and mining parameters (Radwanek-Bąk 2002). This makes the afore-mentioned group of criteria the most diverse and complicated. The analysis of the domestic balance of mineral commodities, has determined that the possible elimination of substitutions is of very limited significance. Among the criteria, those defining the quality of the raw material are the most important. They correspond to balance criteria recommended in Poland or to European standards.

In evaluating the possible applications of a mineral commodity, three classes of deposits should be distinguished: the most valuable, with the mineral commodity of a preferred specific or unique application; of

medium value, with the mineral commodity being broad, multi-directional but more common applications, and the least valuable (mediocre, inferior), with the mineral commodity of a narrow yet common application.

In order to evaluate the frequency of the deposit occurrence the following three categories are proposed: rare on a domestic scale, infrequent at a regional scale, common on a domestic scale.

The size of the deposit should be differentiated into three classes in relation to the distribution histograms for the identified volume of the reserves on a domestic scale. It seems better when assessed separately for each type of mineral, because of real diversity of this parameter.

The most important of the geological and mining parameters are the ratio of the overburden thickness to the deposit thickness (N/Z), the deposit thickness itself, and the presence of barren-rock intercalations in

the deposit profile. The combination of mentioned factors gives a three-level classification for the geological-mining parameters.

The variability of the parameters analysed (quality of the mineral commodity) as well as the geological and mining character of the deposit have been evaluated in three classes: I—of low variability, with a relatively simple geological setting; II—of medium variability, with a complicated geological setting; and III—of high variability, with a complicated geological setting.

Each of the parameters listed above has been given criteria and a scoring system, which allows them to be assigned to one of the following three classes: namely, the highest, medium and the lowest values of the attribute examined. The base scoring system gives: 8, 12 or 16 points. As the importance of particular criteria used for an assessment of geological and mining assets of the deposits vary, they are appropriately ranked (Table 1).

A simple method of valorization combines the ranks assigned the geological criteria, following the formula given below:

$$WP = axk_1 + bxx_2 + cxx_3 + dxx_4 + exk_5 + fxx_6$$

where

WP: summary geological and mining assets,

$a = 0.35, b = 0.1,$ ranks accepted for particular

$c = 0.1, d = 0.15,$ criteria,

$e = 0.2, f = 0.1:$

k_1 – k_6 : assessment of geological and mining assets of the deposits according to the detailed criteria accepted (basic scores).

Thus, the criteria adopted are of a quantitative nature. Application of the system mentioned allows for distinguishing the deposits of high (with more than 130 points), medium (130–100 points) and mediocre (less than 100 points) natural (i.e., geological and mining) assets.

Environmental and planning criteria related to the spatial conditions and concerns of the location of mineral deposits

In order to evaluate environmental and planning constraints the following aspects should be considered:

- location of deposits in the areas under legal protection (national or landscape parks, landscape protected areas, natural reserves, the European NATURE 2000 network, forest complexes, protected soils of high quality, main usable water reservoirs, zones of potable water intakes),
- the distance from built-up areas as well as the permanent infrastructure present in the area of a given mineral deposit which adversely affects the possibilities for deposit management.

The distance from markets is of smaller importance, depending mainly on economic not environmental constraints. Preferences in this respect depend on the type of mineral commodity. A short distance is crucial in the case of deposits of bulk commodities, for which the transportation costs are significant components of the final costs. Although the role of the above aspect varies depending on the current economic situation and ongoing large construction investments, it is generally limited by market economic conditions and with increasing competition from producers. The evaluation of the environmental and planning constrains should be undertaken bearing in mind that even one complicating factor (e.g. degree of built-up area) can influence the final assessment. In extreme cases (areas of the permanent built-up, location within a national park) it leads to a rejection of the deposit from the total proven reserves.

With respect to the environmental and planning impact, the following division of mineral deposits is proposed: deposits available without any constrains, deposits available with some constrains and non-available (inaccessible) deposits.

Table 1 Scoring system for the evaluation of geological assets (minerals and deposits)

Parameter analysed	Quality of the mineral raw material	Range of possible use	Frequency of the deposit	Quantity of identified resources	Geological-mining parameter(s)	Variability of parameters
Weight of the parameter (%)	35	10	10	15	20	10
Score						
I	56	16	16	24	32	16
II	42	12	12	18	24	12
III	28	8	8	12	16	8

Level of certainty

The level of certainty has to indicate the degree of our knowledge on the mineral commodity and its deposit. An estimation of the Polish resources including reserves has been made at the level of a geological study. The reserves explored during detailed research such as a pre-feasibility study, full feasibility study or mining report have been included within the total quantity of resources explored in the geological study. Thus, the total mineral resources include the mineral reserves.

Although the term “geological study” refers mainly to the certainty of estimating a total geological resource, it is also pertinent to the certainty of recognizing the deposit itself and because of that it might be supportive in the assumed goal of the deposit valorization. The level of certainty as well as the quality of available information on deposits can be estimated by a category of the geological study, which refers to the phase of geological research.

In accordance with the stage of geological studies, the following division of resources is made, for a group of analysed raw materials:

- the detailed and general exploration phase—measured (A + B) and indicated (C_1) mineral resources. There are Polish terms corresponding to categories 331 and 332 of the UN International Classification for Reserves/Resources;
- the prospecting phase—inferred (C_2) mineral resource, corresponding to category 333 of the UN classification;
- the prospecting/reconnaissance mineral resource (D_1), according to the Polish classification traditionally connected with reconnaissance phase of the geological research.

According to the UN International Classification of Mineral Resources, both C_2 and D_1 categories are related to the prospecting phase of a geological research and correspond to the inferred resources (Niec et al. 2002). The mineral occurrences prospected in the D_1 category have defined borders. The characteristics of their mineral commodity as well as the geological and mining conditions are known from the investigations so far completed, although a prospecting grid is often irregular. Many of these occurrences have never been prospected in detail because other exploited deposits present in the vicinity satisfied local demands. Given the decreasing availability of deposits and due to the many constraints on their development (sometimes referred to as their conflict character), the deposits that belong to category D_1 should also be protected.

Evaluation of the reconnaissance resource in perspective areas

Evaluation of the reconnaissance resources in the perspective areas should be based on the assumptions and general criteria analogous to those used in the evaluation of the mineral deposits. However, because of low level of knowledge on the geological setting and quality of the mineral commodity, the evaluation of the perspective areas should be carried out in a different manner than it was done in the case of the mineral deposits. The degree of recognition of the perspective areas, and thus the level of certainty of geological information, can be extremely diversified due to the general geological variability as well as the extent of the geological investigations. As a consequence, the borders of such areas are only approximately delimited, the raw material (mineral commodity) quality is not really known and the estimation error is rather high. Moreover, the evaluation of the reconnaissance resources refers to much larger areas than is the case for mineral deposits. Because of this, the method of graded marking is suitable for the valorization of the perspective areas.

The following factors should be crucial in an evaluation of the perspective areas (reconnaissance resources): general characteristics of the mineral commodity with respect to its usability (quality), degree of recognition of geological setting, general geological and mining conditions as well as environmental and planning constraints. The method proposed in this paper corresponds, to a large degree, to the method used by the US Geological Survey (Taylor and Steven 1983; Loyd and Hill 1994), according to which, the evaluation of the “raw material potential” is related to the degree of geological recognition of the area.

In the proposed model, the possibility of existence of mineral deposits (resource perspective) is analysed and classified into three categories:

1. resource potential which defines the natural conditions and “attractiveness” of the given area with respect to the mineral commodity, evaluated on the basis of the traditional geological analysis;
2. level of certainty (reliability and precision of evaluating the resource potential) on the basis of the degree of recognition of the general geological setting;
3. availability of the area in terms of the limitations imposed by legal forms of nature protection and by the presence of infrastructure.

For each of the three domains, a graded marking scheme based on specified criteria has been proposed.

Ad. 1: Resource potential (potential of the mineral commodity)

Evaluation criteria: geological setting and its differentiation; general physical, chemical, technological properties of the mineral commodity and its possible variability; possible applications for the commodity, and—in case of common industrial minerals—the extent of their outcrops or their position in a near-the-surface zone.

Classification

- *High resource potential:* geological setting favours the existence of the deposits of the given mineral commodity; the data available points to the technological attractiveness of the deposits (quality parameters of the mineral commodity are sound and stable, whereas the geological and mining parameters of the deposit are favourable and of low variability); large area of the outcrops or significant extent of the commodity in the near-surface zone. Such areas have a high probability of containing deposits, which might be exploited on an industrial scale.
- *Medium potential of raw material:* the geological setting points to possible occurrence of the deposits of a given mineral commodity and suggests good although variable quality parameters and geological-mining conditions; the area of outcrops is small or the extent of the mineral commodity in a near-surface zone is insignificant. Such areas favour the existence of small deposits suitable for exploitation on a local scale.
- *Low potential of the raw material:* generally, geological conditions exclude or limit the existence of mineral deposits; the mineral commodities with applicable properties are subordinate; the area of outcrops is small and the extent or rocks in a near-surface zone is low; the technical attractiveness of the commodity is low. Such areas favour the existence of sub-economic deposits. This term has been used to contrast it with the term “no raw material perspectives”, which denotes the areas where the geological setting eliminates totally the existence of the deposits of the given commodity. Evaluation of resource perspectives in such areas is not advisable.

Ad. 2: Level of certainty

Evaluation criteria: knowledge of the geological setting of the given area, quantity and scope of information

related to the mineral commodity (premises, signs of occurrences, active or abandoned mining sites, a presence of identified deposits, the level and scope of investigation). Determining the level of certainty at the reconnaissance stage is only of a descriptive nature. The further proposal is for a classification based on the current degree of recognition of geology in Poland.

Classification

- *High level of certainty:* good recognition of the geological setting of the area—at least with the accuracy level required for constructing a detailed geological map of Poland in the scale of 1:50,000; easy interpretation of the geological setting; none or a thin overburden over a potential commodity is; the presence of deposits or mining sites; minimum data available on the quality of the rock raw material or there is a possibility of a quality evaluation by analogy.
- *Moderate level of certainty:* available information of the geological structure is adequate for regional recognition (scale 1:200,000), whereas in the areas with complex geology, difficult access and weak exposure, it should be more specific, i.e. at the level of detailed mapping (scale 1:50,000); none or only a few occurrences of minerals and deposits; no information on the quality of the mineral commodities.
- *Low (doubtful) level of certainty:* the amount and range of geological information is insufficient to evaluate the mineral resource potential.

Ad. 3: Availability of the area

Evaluation criteria: regulations concerning legal protection of the given area; the range and type of the existing built-up areas and infrastructure and infrastructure).

The criteria accepted in evaluating the availability of the area are analogous to those used for the valorization of mineral deposits but only three, instead of four, slightly differently defined classes of constraints have been distinguished here.

Classification

- *Areas without restrictions:* no forms of legal protection of the area or limited protection that can easily be annulled (protected soils, areas of protected landscape), no compact or diffuse built-up areas, no permanent infrastructure. This class corresponds to

the two classes distinguished above when valorizing the deposits (i.e. the deposits with and without a small environmental and planning impact).

- *Restricted areas*: location in buffer zones of national and landscape parks, compact forest complexes, ecological plots, in areas in the “NATURA 2000”—protection system; in diffuse built-up areas, and in the areas of proven main groundwater and surface water reservoirs. This class corresponds to the deposits of high environmental and planning impacts distinguished when valorizing the deposits.
- *Inaccessible areas*: location in national parks and nature reserves, within compact built-up land development or in the land with permanent infrastructure and strategic objects. Such areas must be excluded from an evaluation of their resource perspective.

Results

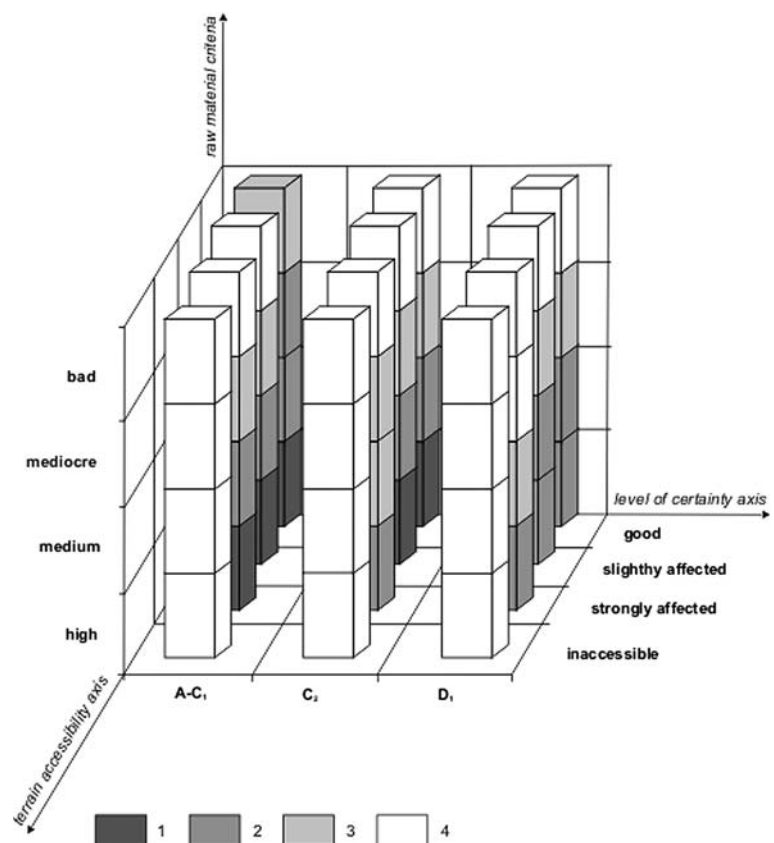
The scheme of the complex valorization of identified and inferred, undeveloped or abandoned deposits is based on the three groups of criteria described above and presented in Fig. 2. As it has been assumed, the valorization discussed allows for the distinguishing of

three groups of mineral deposits and enables grading requirements pertinent to the protection of these deposits. It is also possible to distinguish the fourth group of the deposits, which does not fit completely with the above criteria. Such deposits can be used for local needs.

The first group comprises the mineral deposits, which deserve the best protection. These are the deposits containing the highest, well-recognized geological and mining assets, and are the ones that determine the primary use of the area as a future mining location. Such deposits should be protected at the state level. Information on the most valuable deposits should be also entered into the Global Monitoring for Environment and Security (GMES) system as a part of the European reserves of potential non-renewable mineral raw materials.

The second group comprises the mineral deposits, which deserve amplified protection. These deposits are of good quality, contain the resources important for the given region, and are of expected high geological and mining assets although currently not sufficiently recognized. Such deposits should at first be better recognized and evaluated in the next step. As the outcome of the assessment, the deposit can be left in group 2 or reclassified wholly or in partly into a lower or a higher

Fig. 2 Scheme of evaluation of mineral deposits for the purpose of their protection: 1 deposits deserving the highest protection, 2 deposits deserving amplified protection, 3 deposits protected according to current legislative regulations 4 deposits not deserving any protection



group. To establish the rules for the protection of resources, the deposits with mediocre but well recognized geological and mining assets and localized in the areas without environmental and planning constraints, should be assigned to this group as well. The control over the discussed large group of the deposits should be exerted at a regional administration level. Some of deposits with indicated resources should be mined prior to any other land use activity being determined.

The deposits assigned to the third group should be protected according to the legal regulations currently being in force in Poland. This means that they have to be reported in local municipal plans of land use management. Also, in the case of insufficiently recognized deposits, before deciding on any other permanent land use, such deposits should be recognized in order to identify their more profitable elements. These parts should be exploited prior to other planned investment activities (or sometimes as a part of them) or, at least, such a possibility should be considered. Some deposits, which do not fully satisfy the recommended balance criteria, should only be registered for their possible development in the future, without imposing current protection measures.

As a result of valorization of the reconnaissance resource in the perspective areas, the following classification has been proposed (Fig. 3).

Areas of high resource perspective. For the areas fulfilling the following requirements: (1) high potential + high reliability of evaluation, available without or limited restriction; (2) medium potential + high reliability of evaluation, available without restrictions.

Areas of moderate resource perspective. For the areas fulfilling the following requirements: (1) high potential + moderate reliability of evaluation, available without or with restrictions; (2) medium potential + high reliability of evaluation, available with restriction; (3) medium potential + moderate reliability of evaluation, available without or with restrictions.

Areas of low resource perspective. For those areas of low potential and high or moderate reliability of evaluation, accessible without or with restrictions.

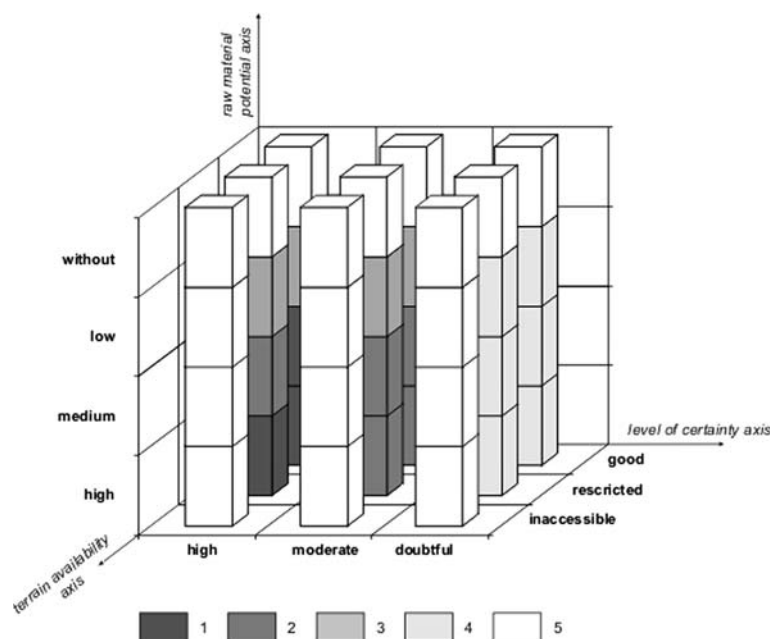
Undefined resource perspective. For the areas accessible without or with restrictions, where the raw material potential cannot be evaluated due to insufficient recognition.

Areas of no resource perspective. (1) For inaccessible terrains, regardless of other criteria, and (2) for the areas for which the geological setting excludes completely the possibility of considering the perspective of given raw material.

Discussion

1. The concept proposed and the method of a complex valorization of mineral deposits and their perspective areas (areas of possible occurrence of deposits) has a multi-criteria character. The procedure of valorization adopted allows for a comparison between deposits of different raw materials using the same, uniform criteria representing three separate groups: geological and mining assets, a level of certainty, and environmental and planning

Fig. 3 Scheme of the complex evaluation of perspective areas: 1 areas of high resource perspective, 2 areas of moderate resource perspective, 3 areas of low resource perspective, 4 areas unrecognized with undefined resource perspective, 5 areas without resource perspective for a given mineral commodity



constraints. Such an approach provides the background for the activities associated with the formal differentiation of the protection range of mineral deposits to be exploited in open pits (crushed and dimensioned stones, ceramic clays, etc.). These activities are based on a legalized access to the most valuable deposits and their perspective areas, and permit negotiations when discussing the future of the deposits of a lesser value.

2. Evaluation is particularly useful in the evaluation of the deposits, which have not yet been managed, and for the deposits, whose exploitation has been abandoned in order to protect the mineral resources left there. The deposits already under exploitation are protected against other non-mining forms of land usage by mining concessions and separate current mining regulations, so their evaluation is only of a comparative character.
3. Including the prognostic areas (the Polish D₁ category of resources) within the procedure of the deposit assessment provides an opportunity for legal protection of the most valuable of them, especially as they have not been protected until now.
4. Evaluation of the mineral raw material perspectives using the proposed methodology allows for including the resource favourable (perspective) areas within the process of landscape planning and, therefore, provides the basis for the protection of highly perspective of them.
5. Information about the most valuable deposits could be entered into the Global Monitoring for

Environment and Security System as a part of a European non-renewable mineral potential.

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