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GIS-BASED SPATIAL ASSESSMENT OF ROCK MINERALS MINING - A CASE STUDY OF THE LOWER SILESIA REGION (SW POLAND)

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Abstract: Mining of rock minerals, constitutes a strong stimulus for economic development and at the same time, can significantly and negatively affect the state of natural environment, roads and well-being of local communities. This paper presents methodology for studies of spatial impact of rock minerals mining in the Lower Silesia region (SW Poland). In the region majority of magmatic, metamorphic and other rock minerals occur in Poland and their intensive mining is an important sector of regional economy. The concept of mining density (mineral production per unit area) has been introduced and the changes of rock minerals mining in the period of the last 8 years (2006-2013) have been analysed and presented graphically with GIS-based methodology. Mining density increased from 2006 to 2011 and decreased from 2011 to 2013. Change in the spatial pattern of mining density between 2006 and 2013, despite comparable volume of rock minerals production, has been identified. In addition proximity of mines to human settlements, nature protection areas and railways (potential transport routes) has been analysed. Comprehensive and coherent information on rock minerals mining for the area of Lower Silesia provided in this study has been used in developing and implementing regional spatial development policy and attaining the balance between the economic needs, nature protection requirements and the well-being of its citizens.

Keywords: rock minerals, mining, regional resource management, GIS analysis, Lower Silesia (Poland)

INTRODUCTION

Mining of rock minerals, dimension and crushed stones and sands and gravels in particular, is a stimulus for economic development and at the same time, when carried

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out in an inappropriate way, can significantly and negatively affect the state of natural environment, transport infrastructure (roads) and well-being of local communities. The problem of environmental, economic, and social impacts arising from increased mining activity, especially in the sphere of environmental impact assessment have been studied by (Vrba and Moldan, 1989; Jordan, 2009; Huang and Wang, 2012; Craynon et al., 2015).

Mining of developed deposits and opening up of new mines is a derivative of the present and the anticipated demand for various types of rock minerals and the location (distance) and size of potential markets. Development of mining operations (quarries, sand and gravel pits) is conditioned by the requirements of nature protection, current spatial development and land use constraints, connectivity to transport networks, geological and mining conditions and other factors (Radwanek-Bąk, 2007).

Knowledge of the current situation and the trends in development of rock minerals deposits and the scale of rock minerals mining provide important information for self-government authorities and their bodies responsible for the coordination of regional management tasks and coherent spatial development policy. This policy, in relation to natural resources management, in Poland, is reflected in strategic documents such as regional spatial development plan and strategy of regional development.

This paper describes a GIS-based methodology proposed for studies of spatial concentration of rock minerals mining on the case study of the Lower Silesia region in Poland. The methodology has been used to study and interpret spatial and temporal changes in rock mineral mining distribution in the period of 8 years (2006-2013). These studies are an advancement and enhancement of research described in (Blachowski, 2014). The proposed methodology is based on density analyses and map algebra operations for spatial modelling of regional mineral resources management in geographical information systems (GIS).

The practicality of GIS based applications for purposes of modelling different types of spatial phenomena, environmental assessment, and optimal location analyses has been evidenced by numerous studies. Notable examples include: Bagdanavičiūtė and Valiūnas (2013) who developed GIS and multi-criteria based methodology for land use suitability analysis, Hyder (2012) who has applied GIS map overlay to develop a model for selecting suitable sites for underground coal gasification. Bathrellos et al. (2012) have used GIS functionality to assess potential terrain suitability for urban planning and industry development, whereas Craynon et al. (2015) have used a GIS-based methodology for identifying sustainability conflict areas in surface coal mine design in West Virgina (USA). Karakaş (2014) has applied the Weighted Linear Combination method in GIS to assess new sources of aggregates based on geological and land-use maps. A comprehensive overview of GIS based analytical methods has been provided in (Malczewski, 2006).

The objective of this work is to provide methodology and derivative information on spatial and temporal distribution of rock minerals mining and its evaluation for shaping up sustainable regional spatial policy with regard to mineral resources management. The study has been done for the Lower Silesia region, which has the greatest reserves and is the most important provider of dimension and crushed stones in Poland.

The paper is structured in 5 sections. The first one introduces the objective, reasons for the applied methodology and provides insight into GIS spatial analysis and its applications in mineral resource management. Section 2 describes the study region. Section 3 characterises the data and methods used in the analysis. The following one presents the results and a discussion on the usefulness of GIS-based spatial analyses for sustainable regional resource management in a spatial planning and environmental protection context. The last section provides the conclusions of the study.

STUDY AREA

The Lower Silesia region, in SW Poland, is the most important region of magmatic and metamorphic rocks deposits in the country (98% of documented national reserves). Numerous varieties of these rocks occur and are mined predominately or only in Lower Silesia. The region's share of magmatic rocks such as: basalts, gabbro, granites, melaphyres, syenites, and metamorphic ones, such as: amphibolites, gnejsses or migmatites used in building, road and railway construction constitutes 95 to 100 percent of national reserves (Koźma and Sroga, 2005; Ney, 2002). In contrast, geological reserves of sedimentary rock in Lower Silesia constitute approximately 3 percent of the Polish reserves. Overall, taking into account all types of rocks, more than half of the national reserves of dimension and crushed stones are located in Lower Silesia (53,3% in 2013) (Szuflicki et al., 2014). Deposits of numerous other rock minerals have also been documented in the region. These minerals, for example: whiteware and stoneware ceramic clays, refractory clays, vein quartz, magnesites, kaolin, feldspar raw materials are often located or exploited only in Lower Silesia (Szuflicki et al., 2014). The region is also characterized by large reserves of good quality sands and gravels (natural aggregates). Deposits of these resources related to glacial water (outwash) sediments and gravel deposits in river valleys are an important part of the national reserves of these minerals (Koźma and Sroga, 2005; Ney, 2003).

Intensive mining of rock minerals, dimension and crushed stones in particular, constitutes an important sector of regional economy accounting for approx. 45% of total production in the country. Extraction of rock minerals from deposits takes place in various parts of the region and with intensity that varies in time with demand cycles. Mining has significant impact on land use and spatial development, exerts pressure on nature protection areas, human settlements and the state of transport networks (mainly roads). Examples of two rock mineral quarries in Lower Silesia in the vicinity of protected area and a populated place are shown in Fig. 1 and Fig. 2 respectively.

Statistics describing changes in reserves and production of dimension and crushed stones and sand and gravels for the 2009-2014 period have been compiled and discussed by Bem et al. (2015). They have pointed to the significant role Lower Silesia plays in the national account of these resources and fluctuations production caused by changes in the demand by building and road construction market.

Fig. 1. Granite quarry with the Ślęża Mt. Landscape Park in the background (photo A. Nowacka, 2009)

Fig. 2. Gabbro quarry near the town of Słupiec

The boundaries of Lower Silesia and location of documented rock mineral deposits in the region, classified into developed and undeveloped ones has been presented in Fig. 3.

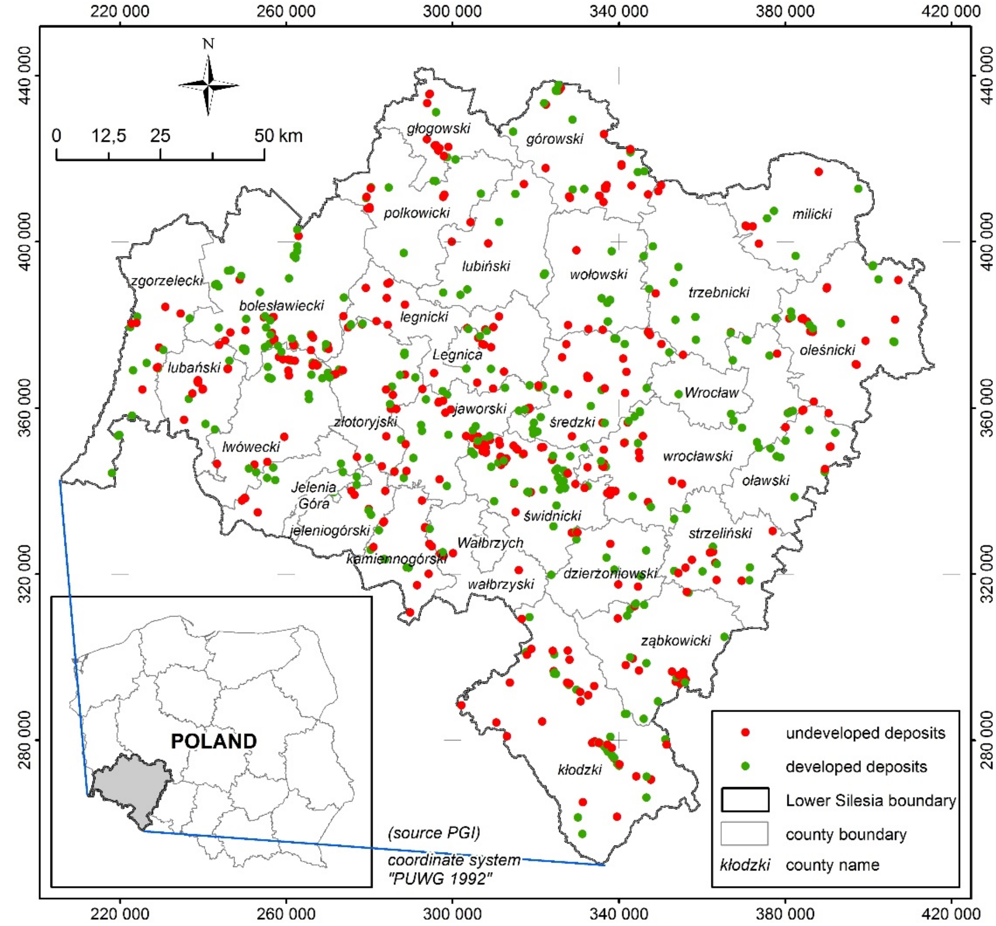

Fig. 3. Location of rock mineral deposits in Lower Silesia and boundaries of the region in Poland

METHODOLOGY AND DATA

The analytical capabilities of geographical information systems (GIS) have been used for analysis of spatial density of rock minerals mining, its changes in time and study of the spatial impact of mining. The GIS database developed for the study stores data on all rock mineral deposits in the Lower Silesia region in the form of polygon and point – polygon centroid – geometries with attributes describing geological reserves and annual production in the 2006–2013 period. The source data for the database include: boundaries of rock mineral deposits from the Polish Geological Institute MIDAS database (PGI, 2015a), data distributed through the Central Geological Database download manager (PGI, 2015b), data maintained by the Lower Silesia Region Geologist and information published in the Minerals Yearbook of Poland (Szuflicki et al., 2014).

This data have been used, in GIS, for:

- calculation of the density of rock minerals mining per unit area in consecutive years with polygon to point and Kernel density functions,
- calculation of the changes of density of mining between the analysed years with raster calculator (map algebra) operations,
- interpolation of the distance from developed deposits (mines) to human dwellings, and for interpolation of the distance from mines to railway rock mineral loading points with near distance function and Inverse Distance Weighted (IDW) interpolation.

Kernel density is a function, which uses a nonparametric nuclear estimator of density proposed by Epanechinkov (1969) in the form of (1):

$$f_{\lambda}(x) = \frac{1}{n\lambda}\sum K_0\left(\frac{x - x_i}{\lambda}\right) \tag{1}$$

Where K_0 – is a quadratic Kernel function (2), λ – is the bandwidth (smoothing parameter), which determines the width of neighbourhood and degree of smoothness.

$$K_0(t) = \begin{cases} 0.75(1 - t^2) & for\ |t| \le 1 \\ 0 & otherwise \end{cases} \tag{2}$$

The function generates, for a given point feature class, a surface of density per unit area fitted to each of the points representing a value of the analysed variable. The input parameters are: location (x, y) of the points, value of the variable in each point, search radius and unit of area.

In the study, the input data included point feature class with locations of rock minerals' mines and the annual output attribute. Density has been calculated for the years from 2006 to 2013. The adopted search radius was 20 km. The maps of mining density– rasters with pixel size 100 x 100 m – obtained with this function have been used to analyse spatial distribution of the density of rock minerals mining in the Lower Silesia region and its changes in time.

The raster calculator uses the map algebra concept (Tomlin, 2008), where raster datasets are used as spatial variables taking part in algebraic, logic and other types of operations to generate new data. An example of algebra operation used in the study is shown below (3):

$$S_R = R_{2013} - R_{2006} \quad (3)$$

where S_R is a raster representing the result of subtraction of two maps representing density of mining for two compared years 2013 (R2013) and 2006 (R2006).

The IDW interpolation function estimates variable values in unmeasured locations using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance (Shepard, 1968). In this case, the function has been used to generate surfaces representing distance between human dwellings and railway loading points based on the data obtained from the near distance operation.

In the study ESRI ArcGIS Desktop Advanced ver. 10.2 GIS software and its analytical extension ArcGIS Spatial Analyst (ESRI, 2014) licensed to the Wroclaw University of Technology have been used. The results are presented and discussed in section 4.

RESULTS AND DISCUSSION

The graphical results of the spatial analyses using the methodology described in chapter 3 are maps that provide spatial information on the density of mining rock minerals within the borders of the Lower Silesia region. The maps prepared for the 8 consecutive years, (2006 – 2013) have been shown in Fig. 4 to Fig. 11 respectively. More intensive colours depict higher density of mining. The data have been classified with the equal interval method and the interval equal to 1 500 Mg/km^2.

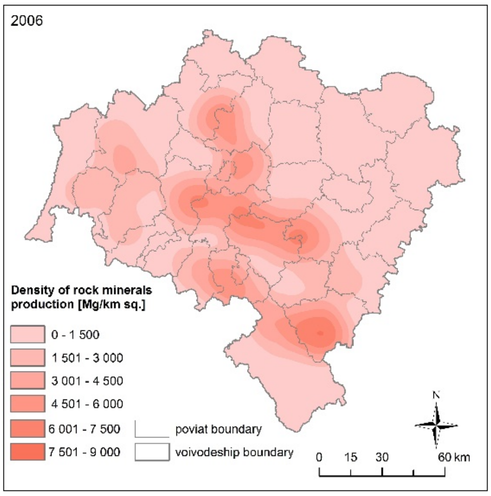

Fig. 4. Density of rock minerals mining in 2006

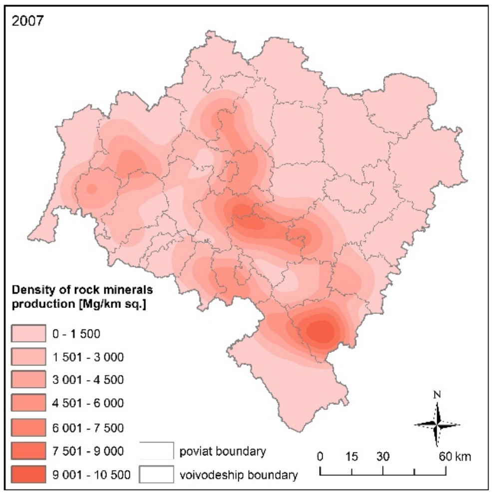

Fig. 5. Density of rock minerals mining in 2007

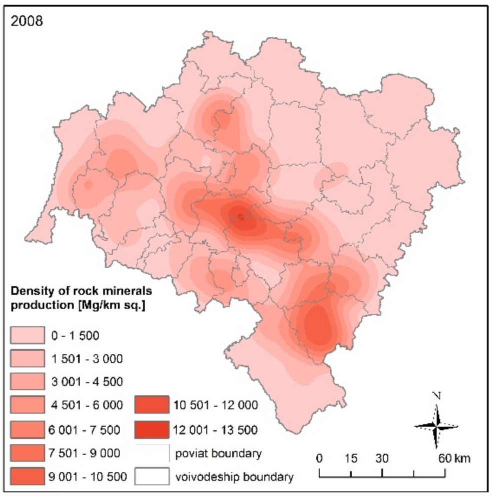

Fig. 6. Density of rock minerals mining in 2008

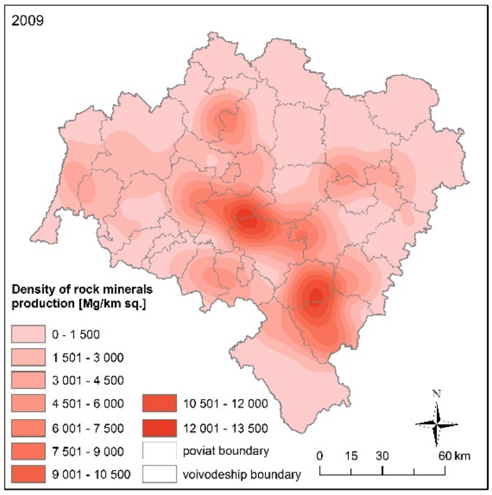

Fig. 7. Density of rock minerals mining in 2009

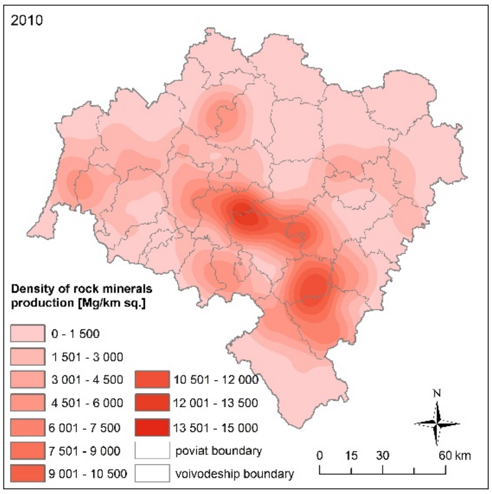

Fig. 8. Density of rock minerals mining in 2010

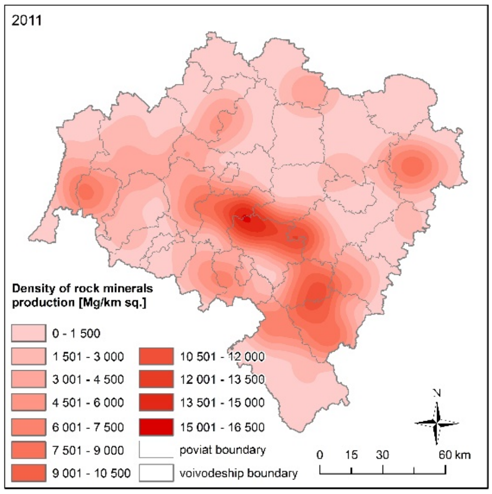

Fig. 9. Density of rock minerals mining in 2011

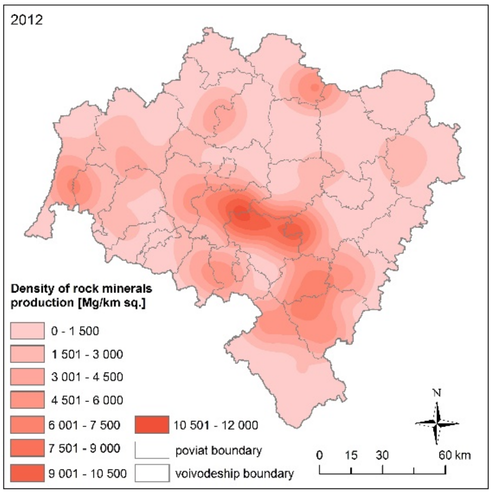

Fig. 10. Density of rock minerals mining in 2012

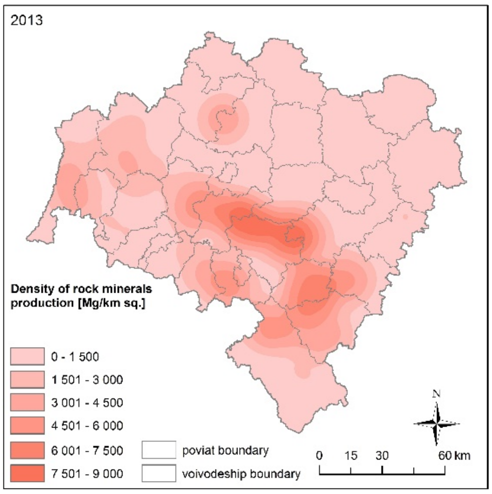

Fig. 11. Density of rock minerals mining in 2013

The maximum and average values of mining density [Mg/km^2] for each year have been given in Table 1.

The density of rock minerals mining rose year to year between 2006 and 2011 when it has more than doubled the maximum value calculated for the first year (Tab. 1). The average density for Lower Silesia rose analogously and reached 1 581,9 Mg/km^2 in 2011 in comparison to 861,0 Mg/km^2 in 2006. In the last 2 analysed years, the density of mining felt to the levels observed in the 2006–2007 period, that is more than twice as fast as the increase noted for the 2006–2011 period. This is concurrent with the production values of these minerals (dimension and rock stones) observed for this period in Poland and for Lower Silesia (Tab. 2).

At the same time, the spatial distribution of the density rock minerals mining has changed in the discussed period. The spatial portrait of mining density in 2013, despite similar scale of mining in the region as in 2006, is different. This has been also shown in Fig. 12, which represents the change of mining density for the 2006–2013 period. The next two figures (Fig. 13 and Fig. 14) show change of mining density for the 2006–2011 and 2011–2013 periods respectively. Warm colours depict areas of increased density of mining and their intensity reflects the scale of growth. Similarly cold colours depict fall in density of mining and their intensity scale of this decrease. The data have been classified with the equal interval method and the interval equal to 1500 Mg/km^2.

Table 3 contains the maximum and average values of density changes for the above-mentioned periods and additionally for the 2006–2009, 2006–2010 and 2006–2012 periods. The maximum growth of density of mining rock minerals between 2006 and 2011 amounted to 9320,2 Mg/km^2.

Table 1. Maximum and average values of the density of rock minerals mining between 2006 and 2013 [Mg/km^2]

Year	2006	2007	2008	2009	2010	2011	2012	2013
Max. density	7539,4	10 121,4	12 151,2	13 154,3	13 544,8	15 209,2	11 090,0	8 846,2
Ave. density	861,0	993,0	1 202,9	1 252,9	1 293,5	1 581,9	1158,9	897,7

Table 2. Production of selected types of rock minerals in Lower Silesia between 2007–2013 [th. Mg] (source Polish Geological Institute)

Year	2006	2007	2008	2009	2010	2011	2012	2013
Dimension and crushed stones	17 891	22 886	25 952	28 116	30 423	38 727	27 847	26 108
Sands and grav-els	11 995	13 049	14 066	14 439	14 505	21 674	13 903	10 024

Table 3. Changes of the density of rock minerals mining between 2006 and 2013 [Mg/km^2]

Period	2006-2009	2006-2010	2006-2011	2006-2012	2006-2013	2011-2013
Max. pos. change	10 558,4	10 113,6	9 320,2	5 988,1	5 385,0	218,5
Max. neg. change	-1 582,4	-2 869,85	-4 301,1	-4 278,5	-5 101,4	-7 495,6
Ave. change	391,9	432,5	720,8	297,8	36,7	-684,1

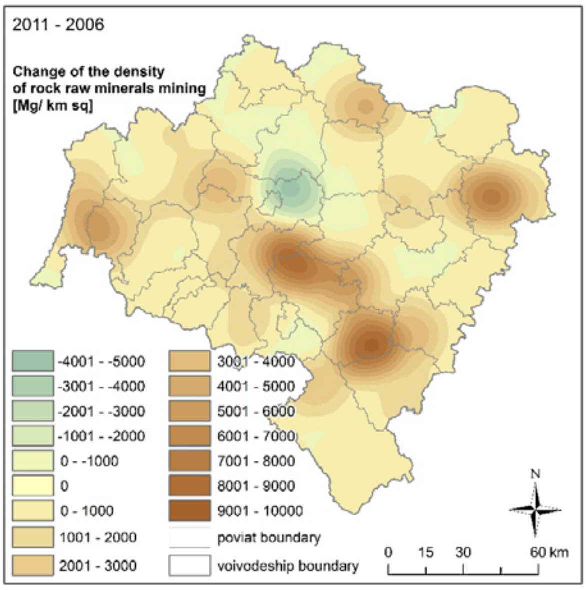

Fig. 12. Change of density of rock minerals mining between 2006 and 2011

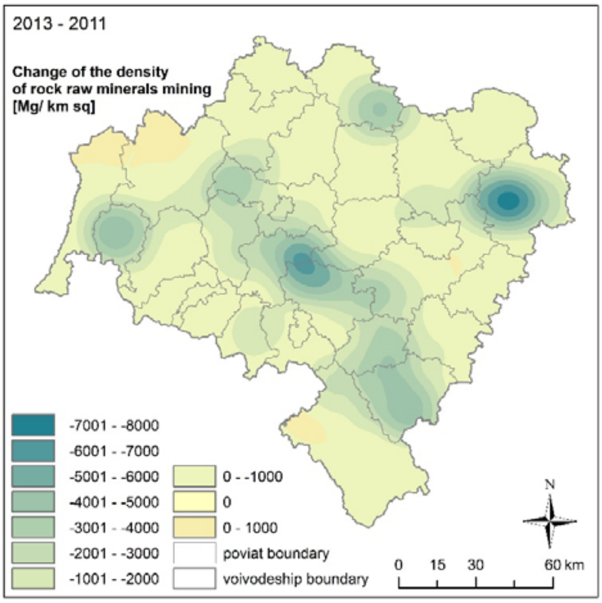

Fig. 13. Change of density of rock minerals mining between 2011 and 2013

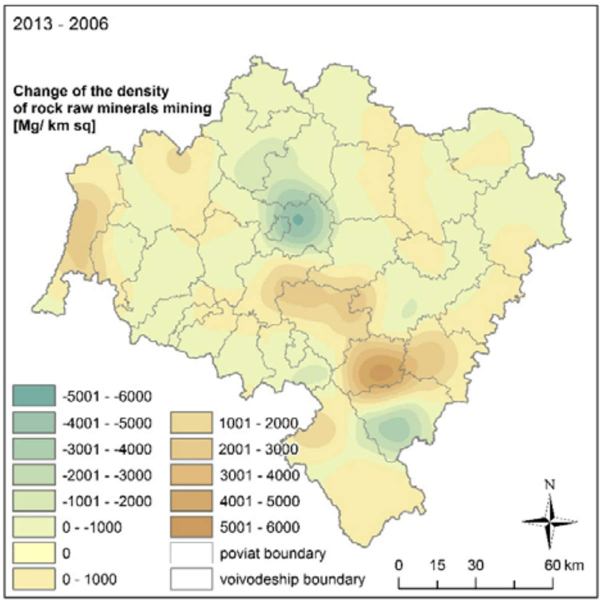

Fig. 14. Change of density of rock minerals mining between 2006 and 2013

The results (maps shown in Fig. 4 to Fig. 11) indicate that the traditional rock minerals mining regions in Lower Silesia (mainly dimension and crushed stones) experienced growth and expansion of mining, depicted graphically by more intensive colours associated with higher values of raster maps representing density and also larger areas of higher mining density. This can be observed for example for the *lubanski*, *swidnicki*, *walbrzyski* and *zabkowicki* counties (county names are shown in Fig. 3). This process lasted until 2011 when record levels of rock minerals production were recorded in the country and in the region (Tab. 1 and Tab. 2). During this period new areas of intensive rock minerals mining in Lower Silesia developed. These were usually associated with opening up of new quarries and sand and gravel pits producing rock raw materials for building and road construction purposes. For example in the vicinity of Wroclaw – the region's capital, i.e. *olesnicki*, *trzebnicki*, and *wroclawski* counties, as well as in the *boleslawiecki* and *dzierzoniowski* counties. This development was the result of forming new and receptive internal markets for rock raw materials, such as large urban centers (Wroclaw being the primary example), construction of new roads, e.g. Wroclaw Motorway Bypass and other ones. Taking into account the role of Lower Silesia, as a major provider of magmatic and metamorphic rocks in the country, forming of large external markets in Poland also played a role. In addition, a slight shift of areas of intensive mining of rock minerals in the eastern and northern directions has been noticed (Fig. 6 to Fig. 12).

After 2011 a systematic decrease of mining density in the region occurred. This was associated with smaller demand for these raw materials in Poland and in the region. The year 2013 has seen a return to the values of mining from the years 2006 and 2007. The decrease of sands and gravels mining is greater than that of dimension and crushed stones. Changes in production levels of other rock minerals are less noticeable. At the same time the spatial distribution of the greatest concentration of mining (highest mining density), despite similar production levels in the first (2006) and the last (2013) periods is slightly different. New places and areas of rock minerals mining developed in the region and some other have lost significance. In the 8-year period, short-term areas of mining activity lasting for several years and associated with periodic exploitation of deposits usually for local (regional) enterprises also occurred. Nonetheless, most of the traditional mining areas have maintained their status. It must be remembered, when interpreting the results, that the Lower Silesia region is characterised by occurrence of individual, large, open-cast rock minerals mines (mainly dimension and crushed stones) with high and very high production and the occurrence of smaller mines, located close to each other and forming clusters that equal the production levels of the former type. Clusters of mines, quarries or sand and gravel pits can be observed for example in the *swidnicki* county, and the valleys of main rivers in the region (*boleslawiecki* and *zabkowicki* counties).

In the context of regional spatial policy in the Lower Silesia, increase of rock minerals mining results in growth of regional economy but also in intensification of environmental and social problems. The first are associated with pressures to increase production and opening up of new mines, actions that are often in conflict with the requirements of nature protection and well-being of local populations. The second with growth of road transport of rock minerals and their products, which in turn results in deterioration of roads having technical parameters inadequate to carry large streams of rock minerals transport, decrease of road transport safety and discomfort of citizens. Therefore, a careful balance between all these factors is needed and a comprehensive information on mining activity for the complete area of the region can help in shaping up the regional spatial development policy.

With this in aim supplementary analyses have been performed and the results of the two of these, (1) distance of mines to human settlements and (2) distance to railway loading points have been shown in Fig. 15 and Fig. 16 respectively. The first one gives insight into areas of pressure caused by the effects of mining on human population, similar analyses have been done for nature protection areas, etc. The second one potential of railways to carry transport of rock raw minerals and decrease the pressure on local and regional road transport network. The first analysis points to the strongest influence of mining on human settlements in major mining regions with exceptions in the *lubinski* and *polkowicki* counties. The second analysis a potential to increase the use of railways to transport rock raw materials especially dimension and crushed stones obtained in the western and southern parts of the region.

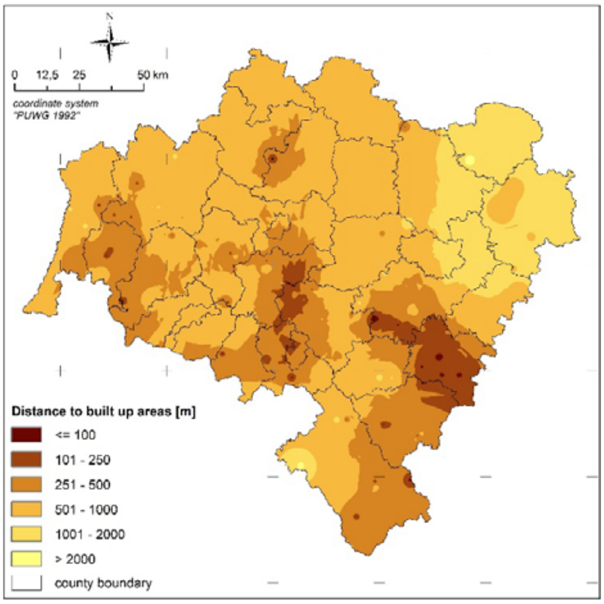

Fig. 15. Distance of mining operations to human settlements

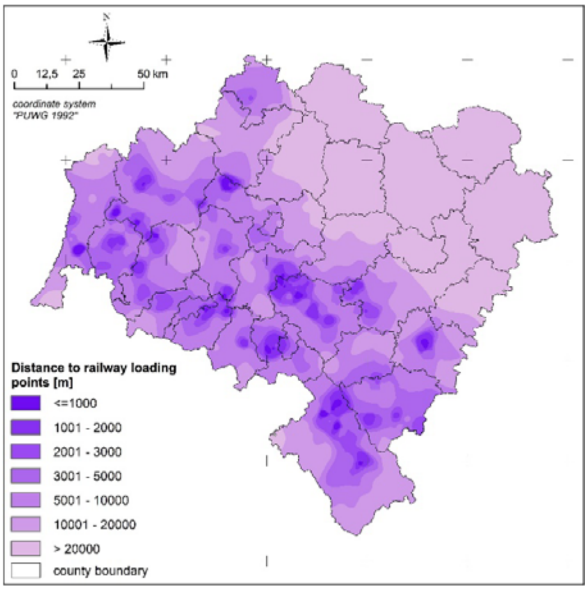

Fig. 16. Distance of mining operations to railway loading points

The results of mining density analyses show that GIS processing provides efficient means to derive and extract spatially referenced information on the state and spatial and temporal variability of this phenomenon and can be applied to other social, economic and environmental issues. The picture of the mining phenomenon shown in the paper on a regional (provincial) scale, through GIS, can be accessed and analysed locally in detail where needed. The derived information provides input for regional spatial management and development policies.

CONCLUSIONS

The paper presented methodology of geographical information systems based modelling for spatial and temporal analyses of the distribution of rock minerals mining on a regional scale. The proposed methodology has been used to analyse and assess rock minerals mining in the Lower Silesia region, characterized by large and diverse reserves of these resources, for the past 8 years (2006–2013).

The results have allowed to investigate spatial changes in the output of rock minerals mining in the region including identification of areas of mining growth and decline.

During the analysed period an intensive and steady growth of mining occurred (until 2011) and an even more intensive decrease of rock minerals production after that year. In the first phase (2006–2011) new, periodic, areas of high concentration of rock minerals mining were observed. The spatial picture of mining density in the year 2013 differs from the 2006 one, despite similar values of the maximum and average density of mining. The following counties: *dzierzoniowski*, *klodzki*, *swidnicki* (central and southern part of the region) and *zgorzelecki* experienced greater amount of mining in 2013 than in 2006 (dimension and crushed stones). Whereas, a decrease was observed in the boundaries of the *zabkowcki* (sands and gravels) and the *walbrzyski* counties.

The database and analytical algorithms that have been developed in GIS for the purpose of this study allow queries and analysis of the condition of rock minerals mining and its influence in the region in a continuous manner providing information for regional self-government authorities responsible for spatial development policy and management.

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