ZAŁĄCZNIK 4
SUMMARY OF PROFESSIONAL ACHIEVEMENTS

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4.1. Education, diplomas and scientific degrees awarded

After the completion of Prince Edward High School (Harare, Zimbabwe) and obtaining the International Baccalaureate Diploma in 1994, I commenced my studies in the field of mining and geology at the Faculty of Mining at the Wrocław University of Technology.

A. Master of Science Diploma

- 28 June 1999, Wrocław University of Technology, Faculty of Mining,
- field of *mining and engineering geology,*
- specialisation: earth resources management,
- professional title of Master of Science,
- thesis title: *Point positioning with RTK DGPS satellite technique for the needs of opencast mining,*
- supervisor: Prof. Stefan Cacoń

B. Degree of Doctor of Technical Sciences

- 29 September 2003, Wrocław University of Technology, Faculty of Mining,
- field of *mining and engineering geology*,
- specialisation: gedynamics, satellite positioning, geographic information systems,
- dissertation title: *Analysis and interpretation of deformations of the surface layer of the Earth's crust in the proximity of designed water reservoir,*
- supervisor: Prof. Stefan Cacoń,
- reviewers: Prof. Michał Mierzejewski, Dr. Sc. Krzysztof Parylak

C. Postgraduate studies diploma in the field of Geographic Information Systems

- 20 November 2004, Wrocław University of Technology, Faculty of Geoengineering, Mining and Geology, Lifelong Education Centre,
- Thesis title *GPS satellite positioning for field mapping of bicycle trails in Lower Silesia*

D. Postgraduate studies diploma in the fields of research projects management and commercialisation of research results

- 18 June 2011, Wrocław University of Technology, Faculty of Computer Science and Management

4.2. Work experience in research institutions

10.2003-1.2005	Wrocław University of Technology, Institute of Mining Engineering, Geodesy and Geoinformatics Division, assistant
2.2005-present	Wrocław University of Technology, Institute of Mining Engineering, Geodesy and Geoinformatics Division, adjunct (adiunkt)
2.2009-7.2009	Norwegian University of Science and Technology, Department of Geology and Mineral Resources Engineering, Trondheim, Norway, visiting researcher
6.2012-9.2012	University of New Brunswick, Canadian Centre for Canadian Centre for Geodetic Engineering, Fredericton, Canada, visiting researcher

On 1 October 2003, I commenced my work at the Wrocław University of Technology as an assistant in the Geodesy and Geoinformatics Division of the Institute of Mining Engineering. Since 1 February 2005, I have been employed in the capacity of adjunct. From 2010, I was performing the duties of the head of the Geodesy and Geoinformatics Division, and on 1 October 2011, I was appointed to this function pursuant to the decision issued by the Dean of the Faculty of Geoengineering, Mining and Geology. On 1 October 2012, I also assumed the function of the deputy head of the Institute of Mining Engineering for scientific research and cooperation with industry. I fulfilled those functions by the end of 2014 when - as a result of reorganisation at the University - the Institute of Mining Engineering of the Wrocław University of Technology was closed. Since 1 January 2015 until 30 October 2016, I have been performing the duties of the head of the Faculty Division of Geodesy and Geoinformatics. Presently (since 1.11.2016) I am performing the function of deputy head of the Division.

Simultaneously, from 15 November 1999, I have been doing part-time job in the Institute for Territorial Development (previously, that is by March 2013 - the Voivodeship Urban Development Office in Wrocław), a self-government organisational unit of the Office of the Lower Silesian Voivodeship Marshall established to fulfil the tasks in the scope of area planning and development at the regional level. At present, I work there in the capacity of the chief specialist for mining and raw material management.

During that time, I participated in several foreign scientific that are listed in **appendix No. 6 point 6.9** to the documentation.

4.3. Indication of the accomplishment arising from art. 16 sec. 2 of the Act of March 14, 2003 on Academic Degrees and Academic Title and on Art Degrees and Titles (Official Journal of Laws, No. 65, Item 595, as amended)

A. Subject of scientific achievement

The basis of the professional accomplishment and application for the scientific degree of *doktor habilitowany* (D. Sc.) is a collection of nine, thematically connected publications in Journals listed in JCR base. The collective title of the cycle is:

Spatial GIS analyses in studies of selected impacts of mining on the environment

B. List of thematically related publications constituting scientific accomplishment

[P1] **Blachowski J.**, (2016) *Application of GIS spatial regression methods in assessment of land subsidence in complicated mining conditions - case study of the Walbrzych coal mine (SW Poland)*. Natural Hazards, , 84:997–1014, DOI: 10.1007/s11069-016-2470-2, (*online 21.07.2016*)
IF = 1.746, 25 MoSaHE (MNiSW) points

[P2] **Blachowski J.**, (2015) *Methodology for assessment of the accessibility of a brown coal deposit with Analytical Hierarchy Process and Weighted Linear Combination*. Environmental Earth Science, 74:5, 4119-4131, DOI: 10.1007/s12665-015-4461-0, (*online 5.05.2015*)
IF = 1.765, 25 MoSaHE (MNiSW) points

[P3] **Blachowski J.**, Milczarek W., Grzempowski P., (2015) *Historical and present-day vertical movements on old mining terrains - case study of the Walbrzych coal basin (SW Poland)*. Acta Geodynamica et Geomaterialia, 12:3, 227-235, DOI: 10.13168/AGG.2015.0020
IF = 0.561, 20 MoSaHE (MNiSW) points
My contribution in this work consisted of participation in formulating the research problem, literature review, development of research plan and conducting research, analysis and interpretation of results, preparation of manuscript and its revision after comments of referees. My individual contribution is 70%

[P4] **Blachowski J.**, Milczarek W., (2014) *Analysis of surface changes in the Walbrzych hard coal mining grounds (SW Poland) between 1886 and 2009*. Geological Quarterly, 58:2, 353–368, DOI: 10.7306/gq.1162,
IF = 1.000, 20 MoSaHE (MNiSW) points
My contribution in this work consisted of formulating the research problem, development of research methodology and plan, survey of literature, analysis and discussion of results, preparation of manuscript and its revision after comments of referees. My individual contribution is 70%.

[P5] **Blachowski J.**, Milczarek W., Stefaniak P., (2014) *Deformation information system for facilitating studies of mining-ground deformations, development, and applications*. Nat. Hazards Earth Syst. Sci., 14, **1677**–1689, DOI:10.5194/nhess-14-1677-2014,
IF = 1.735, 30 MoSaHE (MNiSW) points
My contribution in this work consisted of formulating the research problem, development of research methodology and plan, experimental work, preparation of manuscript and its revision after comments of referees. My individual contribution is 60%.

[P6] **Blachowski J.**, Chrzanowski A., Szostak-Chrzanowski A., (2014) *Application of GIS methods in assessing effects of mining activity on surface infrastructure*. Archives of Mining Sciences, 59:2, 307-321, DOI: 10.2478/amsc-2014-0022
IF suppressed in publication year (5-year IF = 0.519), 20 MoSaHE (MNiSW) points
My contribution in this work consisted of participation in formulating the research problem, survey of literature, development of research methodology and conducting research, analysis and discussion of results, preparation of manuscript and its revision after comments of referees. My individual contribution is 60%.

[P7] **Blachowski J.**, (2014) *Spatial analysis of the mining and transport of rock minerals (aggregates) in the context of regional development*. Environmental Earth Science, 71:3, 1327-1338, DOI: 10.1007/s12665-013-2539-0, (*online 17.05.2013*)
IF = 1.765, 25 MoSaHE (MNiSW) points

[P8] **Blachowski J.**, Ellefmo S., (2012) *Numerical modelling of rock mass deformation in sublevel caving mining system*. Acta Geodynamica et Geomaterialia, 9:3, 379-388
IF suppressed in publication year (5-year IF = 0.606), 20 MoSaHE (MNiSW) points

My contribution in this work consisted of formulating the research problem, experimental and design work, analysis and discussion of results, preparation of manuscript and its revision after comments of referees. My individual contribution is 70%.

[P9] **Blachowski J.**, Ellefmo S., Ludvigsen E., (2011) *Monitoring system for observations of rock mass deformations caused by sublevel caving mining*. Acta Geodynamica et Geomaterialia, 8:3, 335-344
IF = 0.530, 20 MoSaHE (MNiSW) points
My contribution in this work consisted of participation in formulating the research problem, experimental and design work, analysis and discussion of results, preparation of manuscript and its revision after comments of referees. My individual contribution is 60%.

C. Discussion of the research objectives of the publications and achieved results together with discussion on their possible application

The problem I have been raising in my research work concerns the spatial effects of mining, in particular the deformation of the surface of terrains affected by exploitation of deposits. In my summary, the term surface deformation means the effect of mining exploitation on the surface expressed in the values of selected indexes (the basic indexes include: vertical displacement - usually a subsidence, horizontal displacement, tilt, curvature, horizontal strain). The theoretical foundations of the process of deformation of areas affected by mining have been presented e.g. by (Chwastek, 1980; Kratzsch 1983; Knothe, 1984; Kowalski, 2000; Hejmanowski, 2001; Powell and Leighfield, 2002; Kwiatek, 2007, Popiołek 2009; Kratzsch and Fleming, 2011). As far as the above issues are concerned, I have been conducting studies of surface deformations under the influence of mining deposits in complicated geological and mining conditions, as well as analysis of spatial conflicts related to exploitation of mineral deposits. I presented the results of these studies in the series of nine thematically related publications listed above. They constitute the summary of my existing academic and practical achievements, also presented in other works, the list of which can be found in **point 5.2. of Attachment No. 5 to the documentation**. The common element of the above research interests is spatial analysis of selected effects of mining activity on the surroundings in Geographic Information Systems (GIS) also called geo-information systems. The analysis of the available literature (described in the series of thematically related publications) on the research on the state of surface in areas of active and done mining activity, as well as studies on other effects of mining on the surroundings shows that this issue still remains a valid research problem, especially in those fields, where traditional empirical methods may not yield satisfactory results. As far as the research problems described in the published works are concerned, they can be divided, in a simplified way, into those focusing on the observation of displacements on areas affected by mining activity (both active and done) with an increasing role of remote sensing and verification of empirical theories on the basis of the results of such measurements, and into the research concerning the methods of analysis and forecasting of deformation of mining and post-mining areas, e.g. with the use of statistical theories or artificial neural networks in GIS. The studies point to the increased use of cutting-edge numeric techniques for the development and analysis of data regarding the impact of mining activity, including the use of Geographical Information Systems. Together with the development of the methods and functions of spatial analyses and tools for their construction, GIS has become an environment that allows for: formulaton of algorithms used for calculations on spatial data, analysis on spatial variables and spatial relationships between them, etc. In my academic work, I focused on the issues of map algebra, multi-criteria analysis and spatial statistics in GIS. The concept of map algebra assumes that sets of spatial data concerning a given area of research and problem consist of maps (layers), each of them representing one factor, e.g. tilt of the exploited deposit or deposit thickness. Such data constitute spatial variables transformed by functions and operations. Such procedures can be performed on one or more layers and, in the case of a single layer, on its whole area or a fragment of it expressed by a given function. Spatial statistics is based on theoretical foundations of classical statistics taking into consideration the location of the analysed data. The theoretical fundamentals of map algebra and spatial statistics were described e.g. by Berry (1987), Jankowski (1995), Burrough and McDonell (1998), Fotheringham et al. (2002), Werner (2002), Anselin et al. (2004), De Mers (2005), Wong and Lee (2005), Tomlin (2008), Urbański (2008), Berry and Keck (2009), Berry and Metha (2009), Charlton and Fotheringham (2009), Longley et al. (2014), Suchecka (2014). From the point of view of studies on the effect of mining on the surroundings, what is also important is the universality of geo-information systems in combining various types of spatial data originating from various, both primary and secondary, sources. Hence the term Geographic Information Technologies (GIT) encountered in the literature, describing all the methods of obtaining data for GIS and data processing in GIS.

The goal of the series of publications focused on one subject, entitled **"Spatial GIS analyses in studies on the effects of mining activity on the surroundings"** was to study and prove the effectiveness of spatial GIS analysis methods for spatial description and forecasting of surface deformation in complex geological and mining conditions and for various types of mining impact, including limited, in space and time, data resources. I carried out studies on the enhancement of the description of deformation of mining areas on the basis of the above presented theoretical assumptions on three various mining objects. They are characterised by complex and varied geological and mining conditions for underground exploitation of various deposits (black coal, evaporites and iron ore). In turn, studies on spatial analysis of other effects of mining on the surroundings were carried out in the example of lignite and rock raw material deposits.

In order to carry out the subsequent stages of the academic work, it was necessary to study and to explain the effects of mining activity on the surface for various exploitation conditions, i.e.: change of the exploitation system, simultaneous exploitation of many deposits, historic deformations, secondary deformations and analysis of accessibility of useful deposits and spatial distribution of exploitation of many deposits. The following stage of the research work was to develop a geo-information system for the monitoring of the progress of mining, as well as the information system concerning mining deformations to support surface deformation analyses. The fundamental element of the studies was to develop computational models for the influence of mining on surface deformations and the surroundings based on the assumptions of map algebra, geographically weighted regression and the analytical hierarchy process.

In my research work, I have proven the versatility of the approach based on the representation theory using continuous fields (spatial variables in map algebra) in the studies on surface deformation and other effects of mining on the surroundings and their effectiveness in a more accurate description of the phenomenon of deformation of surface affected by mining exploitation in complex geological and mining conditions.

Surface deformations of mining area in the conditions of a change of the exploitation system

Exploitation using sub-level caving mining system used e.g. for widespread deposits with high inclination and low thickness (Hamrin, 1980) is characterised by the appearance of three surface subsidence zones: the caved zone - directly above the exploited deposit, the fracture zone and the continuous deformation zone. The rock material above the exploited deposit moves towards the post-exploitation hole creating a cave-in on the surface (Lupo, 1997; Smith, 2003). The movement of rock material must be controlled to ensure safety of work of a mining plant. I carried out studies on the mining terrain surface deformation, for this method of mining, at Kvannevann iron ore mine in Norway in cooperation with academic researchers from the Norwegian University of Science and Technology and the employees of the mine (Rana Gruber AS). The mining plant is a unique research object due to climate conditions there, geological and mining conditions, method of exploitation and limited access to non-continuous deformation zones. The description of the mine is contained in the publications ([P8][1], [P9]). Together with the change of the deposit mining system from sub-level stoping to sub-level caving and the need to start the observations of surface deformations, I developed a concept system for the monitoring and analysis of surface deformations of mining area integrated in GIS. The pilot project of the system was used in the mine to analyse the condition of the surface and to provide a complex assessment of exploitation safety. The author's solution is based on cyclic GNNS (Global Navigation Satellite System) measurements and networks of controlled points placed within survey lines perpendicular to the exploited deposit surveyed with Total Station (Fig. 1). GNSS observations are carried out in order to control the steadiness of Total Station observation points with reference to the points of the national Norwegian geodesic network. Total Station measurements for periodic recording of movements of controlled points placed in the area of the mine and inaccessible after their stabilisation due to safety precautions. The construction and stabilisation of controlled points are properly adjusted to the terrain and measurement conditions. The results of geodetic surveys are integrated in the geo-information system together with the results of numeric deformation forecasts performed using the Finite Element Methods (FEM) in the form of thematic spatial data (information layers). The system serves as an environment for the analysis of recorded displacements, verification of numeric deformation models, as well as visualisation of results for mining services.

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[1] "P" with a number in brackets within the text, e.g. [P1] indicates a reference to a work listed in the series of thematically related publications.

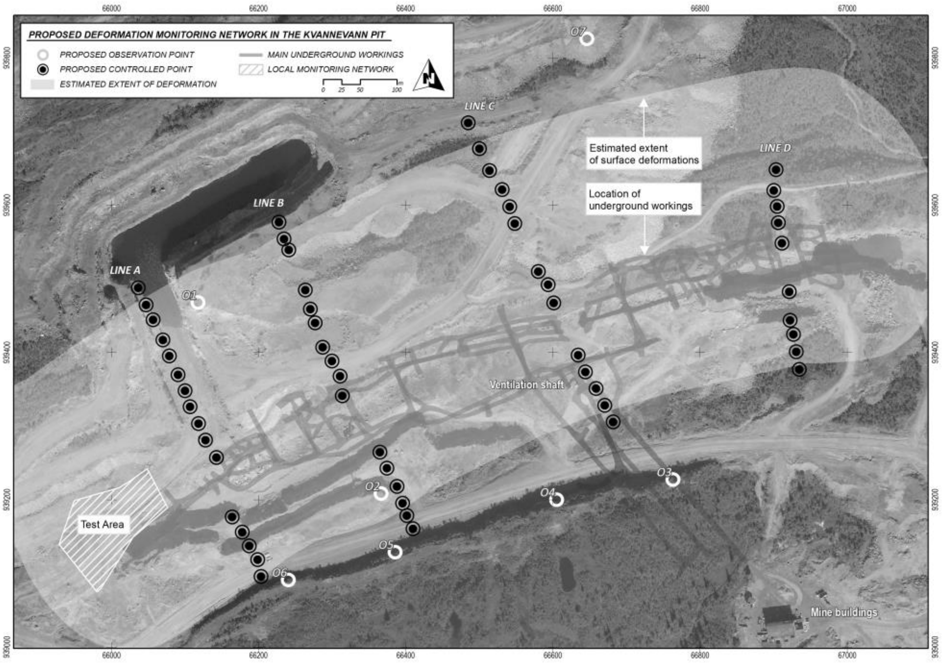

Fig. 1. Locations of controlled and observation points against the background of the production levels, estimated zone of deformation and surface features ([P9])

My numeric computations using the Finite Element Method and surveys in the geodesic measurement and control network, the results of which I published in the works ([P8], [P9]) listed in the series of thematically related publications, showed an increasing range of surface deformation with progress of exploitation on subsequent sub-levels. The values of break angles and limit angles between the zones calculated by me (Fig. 2), and based on these results the modelled extent of surface deformation in individual zones, approx. 300 m for the fracture zone, were used to precisely localize the points of the geodetic control network. The results constitute the base reference values for future analyses. The developed method of the integrated system for the monitoring and analysis of deformations in a geo-information system received a positive opinion of the relevant Norwegian mining supervision authority and has been implemented in the mining plant. My own solution for the monitoring of the condition of the rock mass surface in the aspect of mining safety takes into consideration the conditions resulting from terrain topography, weather conditions and complex geological and mining conditions, including changes in the exploitation system. I carried out my research during academic internships at the *Department of Geology and Mineral Resources Engineering* of the *Norwegian University of Science and Technology* in Trondheim (Norway) under two research grants I received from the Scholarship and Training Fund of the Norwegian Financial Mechanism. I used my experience in the development of an integrated system for the monitoring and analysis of deformations to carry out further studies on the development of a system of information on mining deformation and analysis of surface deformations in the conditions of exploitation of several deposits described in further works being a part of the series of thematically related publications.

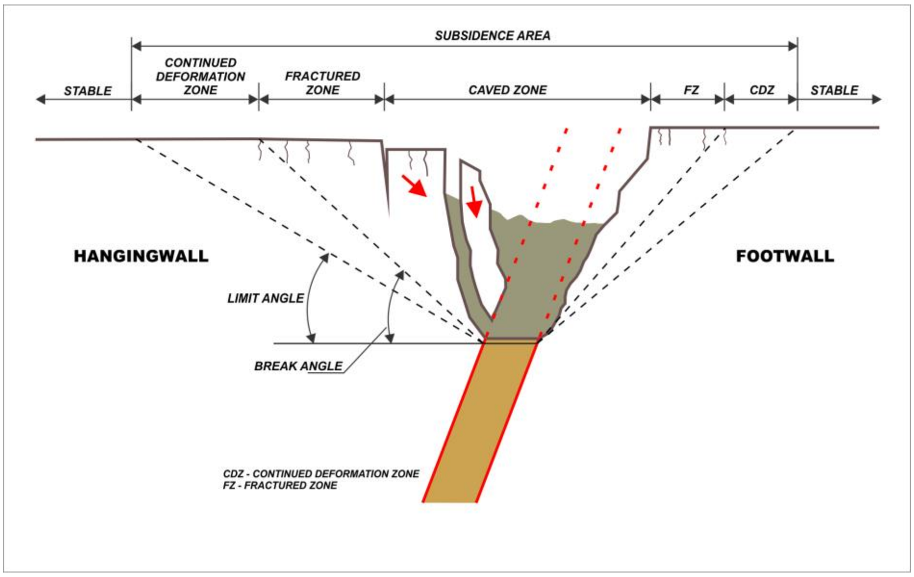

Fig. 2. Rock mass deformation in the sublevel caving (SLC) mining system, arrows point direction of rock material movement ([P8])

Surface deformations of mining area in the conditions of simultaneous exploitation of many deposits

I continued my studies on the improvement of the spatial description of mining area surface deformation using GIS on the case of terrains under the influence of simultaneous exploitation of many deposits. I solved the problem of increasing the accuracy of determination of displacements and basic indexes of surface deformation in such areas in the situation of unevenly distributed and changing in time number of surveyed benchmarks. The research result of these studies is the method of analysis of deformations of terrain surfaces affected by exploitation of deposits in complex geological and mining conditions, based on representation of spatial variables in a continuous structure (raster) and map algebra functions, as well as for varying and irregular number of measurement points. The spatial analysis methodology included the following: (i) determination of partial fields (represented by rasters) of values of vertical and horizontal displacements (spatial variables) together with analysis of accuracy of determination of such displacements, (ii) calculation of total values of displacements, (iii) calculation, on the basis of the above, the values of the following indexes: tilt (*T*), curvature radius (*R*) and horizontal strain (*ε*) for any area of analysis, (iv) analysis of errors in the determination of such values and (v) determination of proper categories of mining areas on the basis of the above.

I carried out the said studies on the area affected by simultaneous underground exploitation of various evaporites and shale gas in eastern Canada during the internship at the *Canadian Centre for Geodetic Engineering* at the *University of New Brunswick* in Fredericton (Canada). I presented the characteristics of the mines in ([P6]). I analysed the accuracy of deterministic and geostatic methods of spatial interpolation and determined partial fields of vertical and horizontal displacements for 15 measurement epochs (1995-2010) using three interpolation methods that describe the surface of deformation most accurately in terms of statistics. The theoretical foundations of interpolation methods have been discussed e.g. in: Shepard (1968), Sibson (1981), Franke (1982), Olea (1999). I determined the summary fields of vertical and horizontal displacements (spatial variables). I used the developed algorithms for the analysis of continuous surfaces with neighbourhood functions in map algebra and on the basis of those spatial variables, I determined the values of the following indexes: tilt (*T*), curvature radius (*R*) and horizontal strain (*ε*) represented as fields of their values. In the case of horizontal deformations, I also took into consideration the direction of horizontal displacements ([P6]). Then, I determined the categories of mining terrain, made a classification of the terrain and on the basis of the above, carried out an analysis and assessment of the effect of complex mining on residential buildings on the surface. Example subsidence surfaces obtained using various interpolation methods, presented with the contour line method are shown in Fig. 3, tilt (*T*) values are presented in Fig. 4, and the map of categories of mining terrain in respect of the selected (*T*) index is presented in Fig. 5.

Determination of displacement fields on the basis of the sum of surfaces representing partial displacements for subsequent periods allowed me to solve the problem of a small number of common points (46) between the first and the last measurement epochs, as well as to obtain value surfaces of basic deformation indexes for the period of 15 years of mining activity, including the analysis of the dynamics of changes in time. The maximum calculated values of deformation indexes for shift surfaces obtained using various interpolation methods are presented in Table 1. The maximum value of the tilt index was in the range from 1.5 mm/m to 2.5 mm/m for radial basis function characterised with a sharper behaviour of the function near measurement points than the two other methods. The value of horizontal strain was in the range from 0.7 mm/m to 1.0 mm/m. In turn, the maximum value of the curvature radius was between 23.4 km and 38.6 km depending on the method.

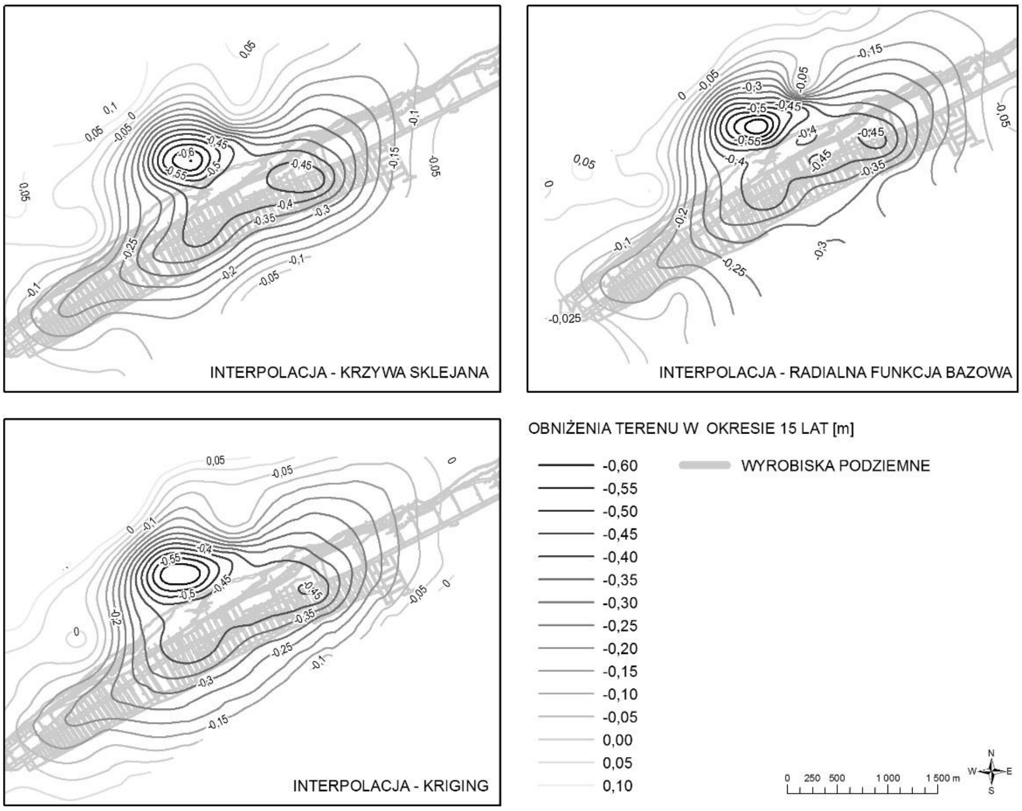

Fig. 3. Isolines of subsidence surfaces during 15 years of mining, obtained with three interpolation methods: spline (top left), radial basis function (top right), ordinary kriging (bottom left), subsidence values are given in [m]

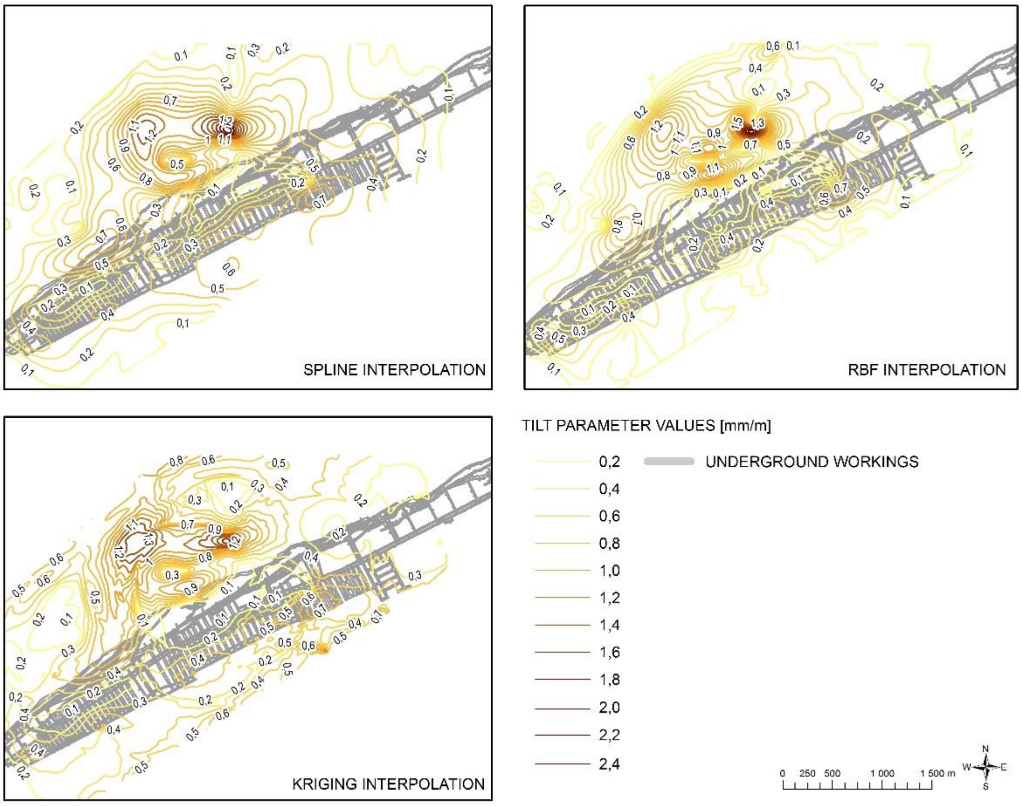

Fig. 4. Isolines of tilt parameter surfaces during 15 years of mining, obtained with three interpolation methods: spline (top left), radial basis function (top right), ordinary kriging (bottom left) ([P6])

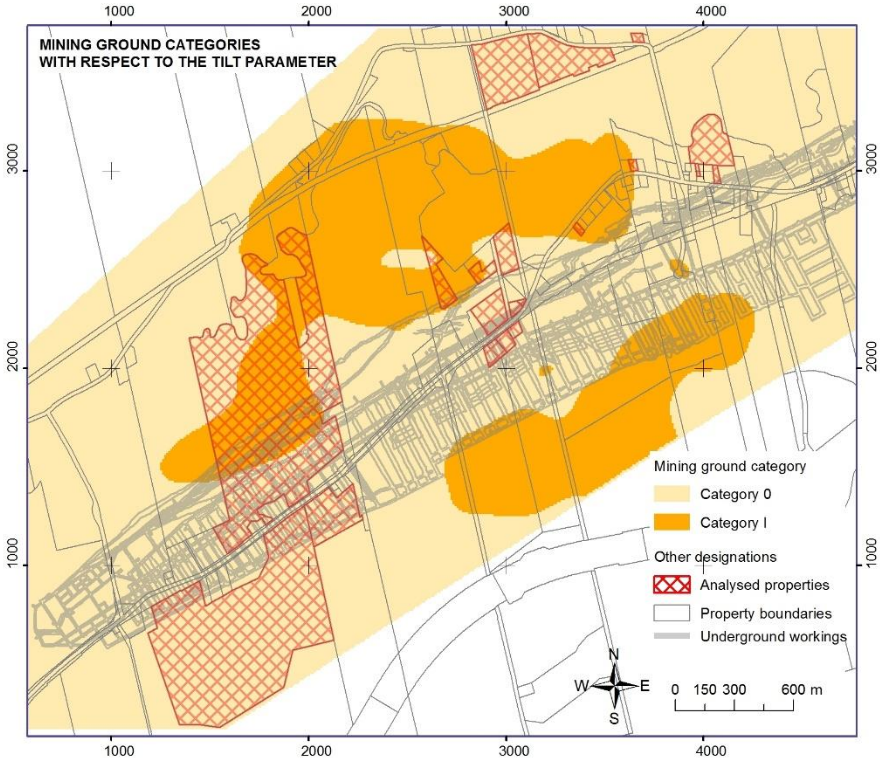

Fig. 5. Map of mining area risk category with respect to the tilt parameter ([P6])

Table 1. Maximum values of deformation parameters ([P6])

Parameter	Spline	Radial basis function	Kriging
Tilt [mm/m]	1.8	2.5	1.5
Radius of curvature (R) $^{*)}$ [km]	-30.6	23.4	-38.6
Horizontal strain [mm/m]	0.7	1.0	0.8
$^{*)}$ „-”sign depicts concave surface			

I determined that the mining activity had no effect on the condition of buildings on the surface. The obtained values of deformation indexes suggested categories 0 and 1 of the mining terrain, whereas the structure of the buildings determined as a result of field inventory corresponded to category 2 according to the adopted Polish classification of building resistance in mining areas ([P6]).

Practical results of my studies are: verification of the method on an actual mining object and proving, on the basis of calculations, that underground exploitation of evaporites had no effect on the condition of buildings on the surface. The excavation of shale gas also had no effect on surface displacements in the analysed period. The developed spatial analysis model in GIS enables to determine the fields of values of basic deformation indexes for any point in the discussed area and to analyse the accuracy of determination of displacement fields. It also allows to study the effects of underground mining on the terrain surface and buildings erected thereon for various deposits and mining conditions, as well as for various data acquisition methods (classic geodetic surveys, remote sensing measurements).

Information system on mining deformation

In the result of the analysis of the literature concerning studies of mining influence on the surrounding area carried out in both Polish and foreign scientific centres, I found that studies on deformation of the surface of mining areas using GIS concern only some aspects of spatial information management and spatial data modeling. On the basis of such studies and experience in analysing mining areas with the use of spatial analyses, I developed an architecture for a universal system of information on mining-induced surface deformations (Deformation Information System) in the geographic information systems environment ([P5]). Then, I developed a system to support studies on changes of the terrain surface occurring during the operation of *Wałbrzyskie Kopalnie Węgla Kamiennego* (*Wałbrzych Black Coal Mines, WKWK*) and after their closure. The structure of the system is modular and comprises components containing algorithms developed in order to support studies on deformation in the areas of active and former mining activity. The basic components of the system are as follows: (1) geographic database, (2) module for searching and extraction of data, (3) module for spatial data analysis, (4) module for geological data modeling, (5) module for data classification, (6) module for data visualization, and (7) module for spatial data encoding.

The core of the structure is the spatial data database, which I had been developing since the beginning of the work on the mining geo-information system (Blachowski, 2008). It constitutes a repository of spatial data concerning the analysed mining activity and its impact on the condition of the surface and objects on the surface. The basic application schemes include vector and raster spatial data structures used for the storage of source data (e.g. lists of benchmarks, lists of heights and displacements of benchmarks in levelling lines, results of other geodesic field surveys, data from satellite observations, geological and mining documents from mining plants, archive mining plans and maps, coal excavation levels and mining infrastructure underground and above ground, as well as other materials. The database contains catalogued thematic classes of spatial objects developed as a result of digital encoding of the above materials with spatial location of deposits, parcels and excavations, as well as related attribute information (including system and period of exploitation, deposit thickness, etc.), spatial data on the location of shafts, protection pillars, geological layers, tectonic faults, digital elevation models and others, such as data on former and current land development. Moreover, it is used to manage sets of derivative data with results of analyses and calculations. I presented a complete characteristics of the database in Blachowski (2008) and Blachowski and Stefaniak (2012). It is, in my opinion, the most complete and extensive digital database of knowledge on the exploitation of black coal in Wałbrzych.

The individual modules of the system contain algorithms and analytical functions I have developed for the purpose of deformation studies. The module for data search and extraction (2) is equipped with tools calculating parameters for a given region as, such as: area, thickness of exploited deposits, employed deposit excavation systems, exploitation period, mean value of surface subsidence determined according to Knothe's theory. Other functions are used to determine other deformation factors, such as seam or parcel inclination, depth under the surface of the terrain or aspect. The data application scheme I adopted is based on raster structure and the results of analyses are returned as fields represented by raster cells with a preset resolution. The value of a pixel represents the averaged value of the analysed parameter in a given location. For example, the raster of depth of the seam under the surface of the terrain is calculated by generating a numeric model of the iven seam on the basis of data collected from the database of the system and calculation of the differences against the numeric model of the terrain.

The module for spatial data analysis (3) includes functions for the determination of vertical and horizontal displacement fields on the terrain surface on the basis of the results of geodesic surveys, as well as algorithms for the calculation of value fields of basic deformation indexes for the surface of area affected by mining exploitation, i.e. tilt, curvature (scheme of procedure is shown in Fig. 6) and horizontal strain. The fields of displacement values are calculated for the values of parameters of adopted interpolation functions, which generate the smallest estimation errors determined on the basis of cross validation. The algorithms for the determination of deformation indexes as input spatial variables employ surfaces representing displacement fields. In the calculations of the value of tilt for a cell (pixel), values of cells from the selected range (its neighbourhood) are taken in consideration.

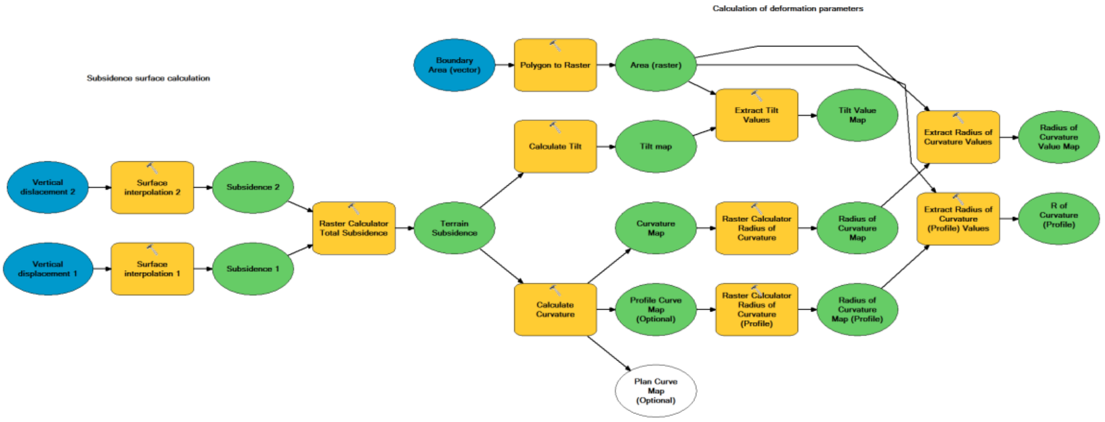

Fig. 6. Scheme of calculation procedure for tilt and curvature deformation parameters ([P5])

The module for data modeling (4) is based on geostatic interpolation functions for the generation of spatial (3D) geological models with the assumed combination of three types of data: data on geological formations, boundary surfaces and surfaces of tectonic faults. The assumptions together with spatial models developed in the example of WKWK have been presented in (Blachowski and Milczarek, 2011), as well as in ([P5]) included in the series of thematically related publications.

The module for spatial data classification (5) contains tools for classification and mapping of areas corresponding to the categories of mining terrains according to the classification with regard to one or more deformation indexes used in Poland.

The visualisation module (6) contains e.g. two- and three-dimensional spatial schemes of visualisation of mines and seams classified in accordance with the system of attributes stored in the database, e.g. mining system (Fig. 7).

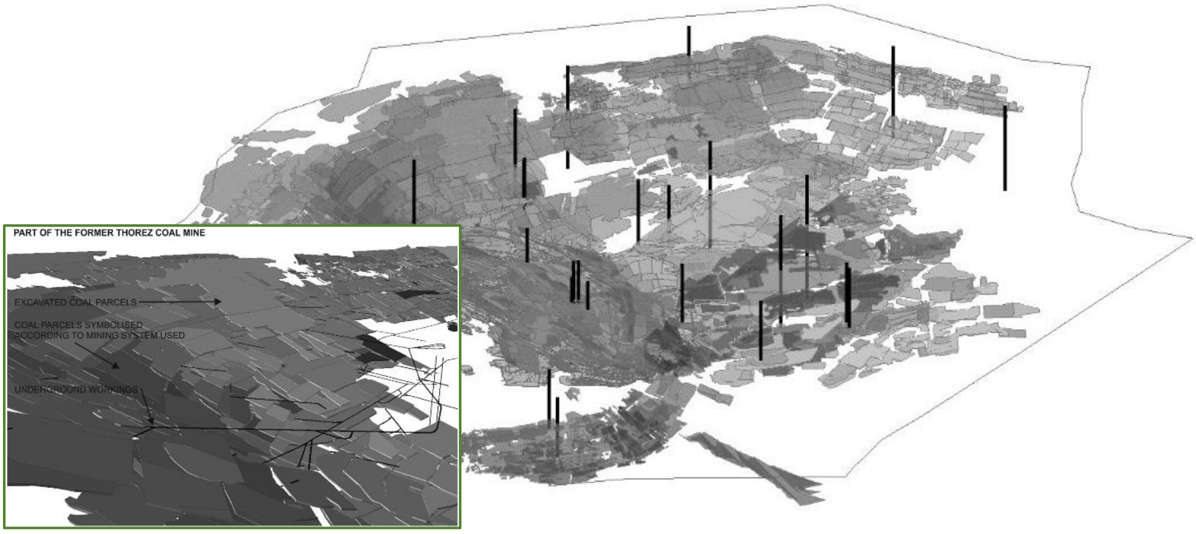

Fig. 7. Spatial visualisation of GIS database storing underground infrastructure of the former Walbrzych Coal Mines (visible: coal parcels, mining shafts, boundaries of former mining grounds) ([P5])

I have been developing and adding new analytical functions to the system. I used the database and the functions of the system in the studies on mining terrain displacement in Wałbrzych during and after exploitation. I published the results of the studies in articles from the thematically related series ([P1],

[P3],[P4]) and others, e.g. (Milczarek et al., 2017). The system's architecture is scalable and its functions can be applied to other underground mining sites.

Historical deformations of mining area surface

Continuing the studies on the impact of mining activity on the surrounding in GIS, I solved the problem of determination of historic deformations of terrain surface in the conditions of limited availability of spatial data ([P4]). Based on the data gathered in the database of the system of information on mining deformations ([P5]), I determined the effects of longtime underground excavation of black coal on the condition of the surface of selected fragments of mining areas in Wałbrzych and I carried out a comparative analysis of the obtained results using the methodology developed in GIS with results of calculations based on Knothe theory (Kowalski and Jędrzejec, 2000). The period of studies encompassed 123 years (1886-2009). The methodology developed by me included the following: (i) development of digital elevation models (DEMs) on the basis of source topographic materials (archive German topographic maps - Meßtischblätter), (ii) analysis of the accuracy of determination of DEMs and difference between DEMs, (iii) comparative analysis of vertical displacement fields, (iv) interpretation of changes to the surface of the fragment of former mining areas in Wałbrzych.

I developed the DEMs of the terrain surface on the basis of the contents of topographic map of 1886 (the oldest one available) as a result of vectorisation of the map and interpolation of height data and the DEMs in the form of a Triangulated Irregular Network (TIN) of 2009. The contour interval of materials of 1886 is 5.0 m and, in the selected areas, 2.5 m. In order to generate DEMs of a historic surface, I used a modified interpolation function developed by (Hutchinson and Dowling, 1991). I calculated the difference in the height of NTMs between two epochs (1886 and 2009) using map algebra operators. The accuracy analysis revealed an error in the determination of height changes at the level of ±2.9 m. I determined the horizontal accuracy, being a derivative of the accuracy of input materials, vectorisation errors and characteristics of interpolation functions, on the basis of the comparison of the set of common locations with known coordinates. It is smaller than the adopted resolution of DEMs and the outcome displacement field (size of the raster pixel: 40 m). The maximum values of subsidence calculated for the two analysed parts of the former mining areas of WKWK (A and B) are -0.2 m and -0.3 m per annum. According to my calculations, the maximum height increases were +52 and +63 (±3 m). Areas of positive changes in height correspond with anthropogenic forms of the terrain (spoil tips) that occurred in that period. The determined deformation surfaces are presented in Fig. 8.

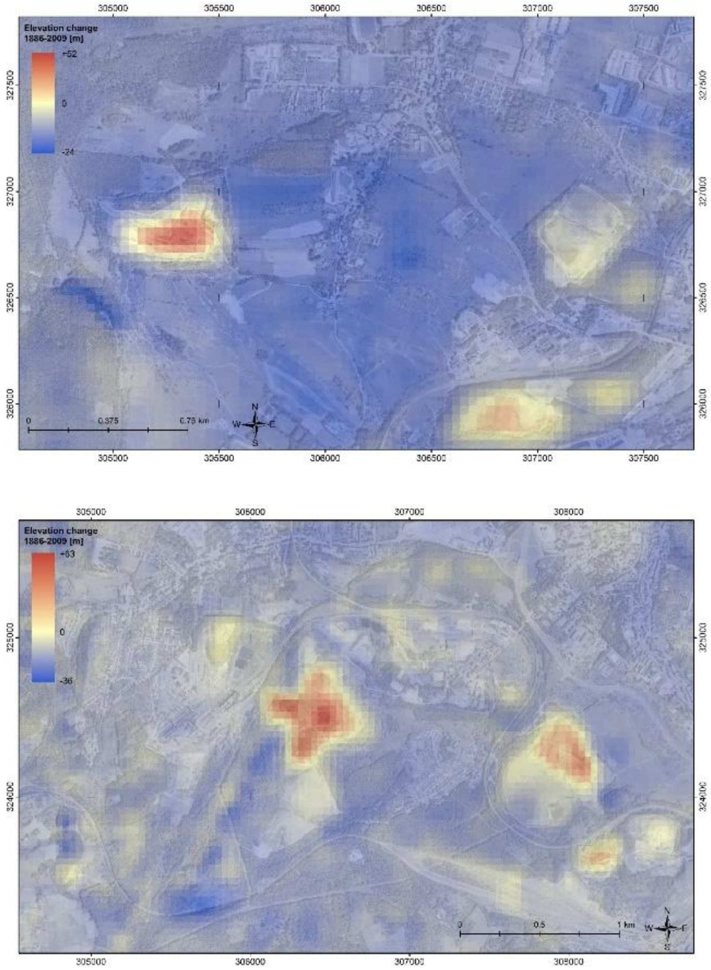

Fig. 8. Surface height changes in the 1886–2009 period, upper for area A, lower for area B ([P4])

The observed positive changes in the terrain height do not mean that it was not affected by subsidence caused by mining exploitation at the same time. I analysed this issue in further stages of my studies ([P1]). I correlated the surface subsidence fields (without areas of positive changes in height) with the results of the forecast prepared by Prof. Kowalski's team on the basis of the modified Knothe's theory (Kowalski and Jędrzejec, 2000). I obtained correlation of 0.90 between spatial variables - rasters representing both calculated and forecast subsidence. I came to the conclusion that the distribution of subsidence values in both analysed displacement fields is not convergent in all aspects. The maximum value of differences between spatially co-occurring raster cells is ±12 m and the mean value equals -0.6 m. In this way, I was able to show the variability of terrain subsidence surfaces that are not as uniform as it would result from empirical prediction. Fig. 9 presents sample maps of subsidence calculated using map algebra functions and in accordance with classical theory. The values of subsidence that I obtained reach -24 m, whereas according to the calculations based on empirical assumptions reach – 18 m.

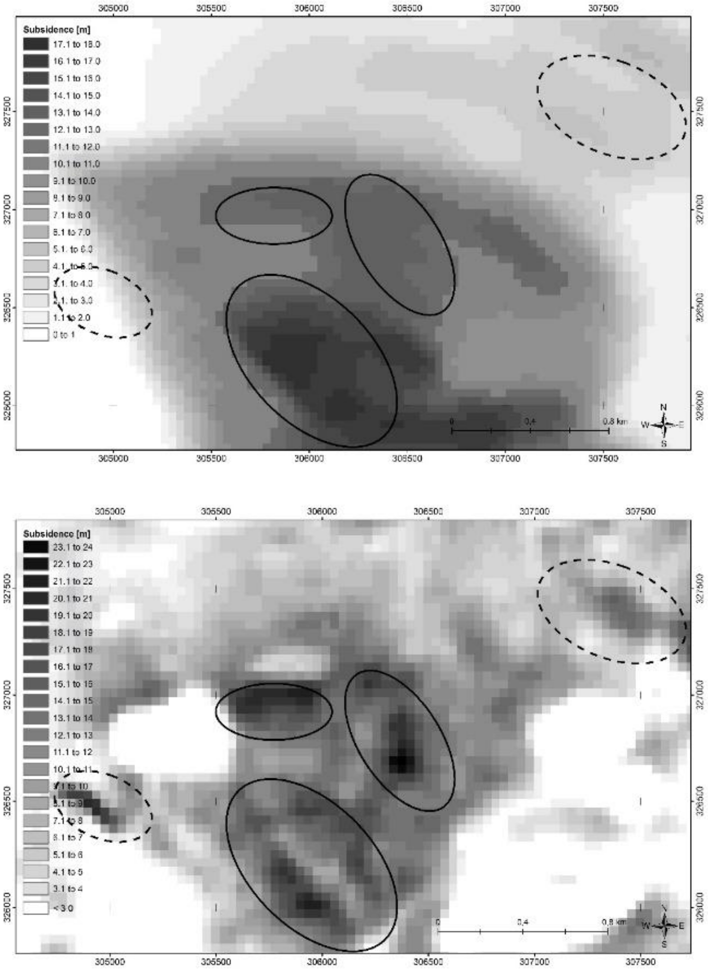

Fig. 9. Subsidence predicted using the modified Knothe method (based on Kowalski and Jędrzejec, 2000) (upper) and subsidence calculated from GIS analysis of DEM raster maps (lower) ([P4])

As a result, I obtained fields representing historic changes in height over the period of 123 years of mining activity and thereafter for the area of Wałbrzych. I proved that subsidence of the surface of terrains affected by underground deposit excavation in difficult geological and mining conditions (numerous, steep seams with varied inclination and thickness) are varied and sometimes difficult to determine using methods based on empirical assumptions. My methodology of calculating displacements on the basis of map algebra functions can be used to verify such displacements. In most cases, it provides a more accurate spatial image of surface deformations. In particular, as in the example of Wałbrzych mines, it concerns longtime exploitation on a large area, as well as spatially and time-limited sources of data on height changes. The results depend on the quality and accuracy of source data. Apart from scientific value, the results are also a source of information for administration workers carrying out observation of former mining areas, their revitalisation and re-development.

Surface deformations of mining area in complicated geological and tectonic conditions of exploitation

In the further stage of my academic work, I studied the impact of mining activity on the surroundings with the application of spatial statistics. I evaluated the usefulness of spatial regression methods in the analysis of the effect of deformation factors on surface displacements. I employed the Geographically

Weighted Regression (GWR) functions for statistical determination of the causative factors of surface deformation affected by mining exploitation on the size of the observed surface subsidence. In the next step, I used them to predict surface displacements on areas that had not been covered by geodesic observations, and for which the determination of displacements using a traditional method was otherwise impossible. One of the examples of such areas are waste dumps on the surface as a result of mining activity and other anthropogenic forms of terrain, which I identified in my previous studies.

Geographically Weighted Regression is a method of spatial regression, in which by matching regression equations with each object with a known location in a set of spatial data, local models of the phenomenon are developed. The computational model takes into consideration spatial variability of relations between the analysed factors. If the general regression equation is presented as (1):

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{21} + \cdots + \beta_m x_{mi} + \varepsilon_i \tag{1}$$

where:
y_i – dependent variable at *i* location,
x_i – independent variables,
β_i – model coefficients,
ε_i - error,
i = 1 to m.

The form of this dependence for Geographically Weighted Regression is (2):

$$y_i(u) = \beta_{0i}(u) + \beta_{1i}(u)x_{1i} + \beta_{2i}(u)x_{2i} + \cdots + \beta_{mi}(u)x_{mi} \tag{2}$$

where:
$\beta_{0i}(u)$ expression that means that the coefficient describes the relation at *u* location and is specific for that location. The value of *y* dependent variable in *u* location is determined on the basis of the available measurements of x_i independent variables for that location.

Theoretical foundations of the Geographically Weighted Regression have been presented in e.g.: Brundson et al. (1996), Fotheringham et al. (2002), Charlton and Fotheringham (2009). I have reviewed the available literature on the subject and found that such methods had not been used in the studies on the impact of mining activity on the surroundings before ([P1]). I analysed seven potential factors of mining surface deformations - independent variables in the model, i.e.: thickness of seams, depth of seams underground, inclination of seams, DEM, distance from parcels and mining system. I identified four first factors to be statistically significant and most accurately explaining the vertical displacements - the dependent variable in the model. I processed the data representing independent variables in the model using the system of information on deformations, as well as database of the system ([P5]). The subsidence area (75.8% of the total area), calculated on the basis of comparison of numeric models from the years 1886 and 2009 was the set of test data and the dependent variable in the model ([P4]). As a result, I determined the subsidence in the surface of areas affected by underground exploitation of black coal, on which positive anthropogenic terrain forms have been formed. In the analysed area, they comprised almost 1/4 of the area (24.2%). Those terrains were not covered by geodetic observations, therefore the determination of subsidence caused by mining activity in a traditional manner was not possible. The best model of the Geographically Weighted Regression was characterised by the value of R^2 model matching coefficient equal to 0.69. This is a good value resulting from the simplifications used in the calculations due to multi-seam nature of black coal deposits in Wałbrzych, as well as complicated geological and mining conditions. The simplifications consisted of summing up the thickness of seams and adopting the mean inclination and mean underground depth of coal deposits. According to my calculations, the values of subsidence in areas not covered by measurements are from -0.6 m to -14.80 m. On this basis, I developed a hybrid map of subsidence for the whole analysed area. It presents subsidence areas determined on the basic of differences between digital elevation model surfaces and subsidence within the boundaries of spoil tips and other anthropogenic forms calculated using the constructed geographical regression model (Fig. 10).

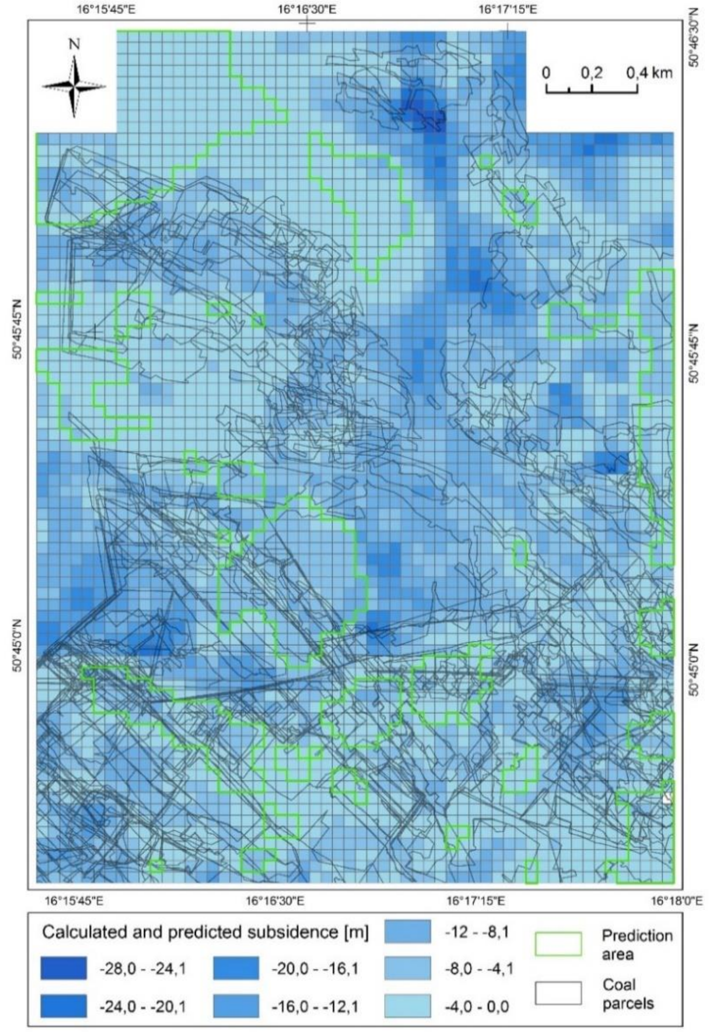

Fig. 10. Hybrid map of calculated subsidence and subsidence predicted for the elevated parts ([P1])

I have carried out research within National Science Centre Project headed by me and titled *„Development of a numerical method of mining ground deformation modelling in complex geological and mining conditions*". My studies contributed to the development of calculation methods and predicting of mining-induced surface displacements, which are based on the continuous field theory of surface representation, map algebra and spatial statistics in GIS. Those methods are useful in complex, complicated geological and mining conditions, regardless of the deposit type and exploitation method, especially in the situation of limited availability of measurement data. I continue my analyses in this field taking into consideration additional independent variables in the example of objects of active and former mining activity.

Secondary deformation of mining area

The following stage of my research work consisted in the analysis of the effects of underground mining activity in Wałbrzych in the final stages of exploitation of black coal and after the end of mining activity. I analysed measurement data from three epochs of levelling surveys (1972, 1993, 2014) using various interpolation functions and self-developed procedures of spatial data modeling (map algebra). I determined the spatial nature of vertical displacements in mining areas over the last two decades of exploitation (1972-1993), at the end of exploitation and after the end of exploitation (1993-2014). I presented the results of the studies employing my own methodology of spatial analyses in GIS addressing the problem of spatially limited and time-limited set of measurement data, as well as the characteristics of the area of the research in ([P3]). I obtained particularly interesting results for the second of the analysed periods. The results point to a varied nature of vertical displacements and occurrence of subsidence and elevation of the terrain surface. The areas with the highest surface elevation values are spatially convergent with the areas of the largest subsidence in the first period (1972-1993). The obtained height changes are within the range from -0.002 m/year to +0.009 m/year (Fig. 11). The values of such displacements are one or two magnitudes smaller than the values for the exploitation period. The difference between the maximum values of subsidence and elevation is 0.237 m. The occurrence and varied nature of such movements suggest an incomplete process of rock mass stabilization in the post-exploitation period and a delayed reaction of the rock mass to the return of the groundwater table to its original condition after the end of the excavation. The groundwater table in the former Wałbrzych mines stabilised circa 2000 (Fiszer, 2003). Currently, I continue to study this phenomenon using satellite radar interferometry (InSAR) and spatial regression (Milczarek et al., 2017). The use of satellite data and InSAR technology allows me to track surface changes in shorter intervals and more precise determination of the dynamics of the secondary deformations.

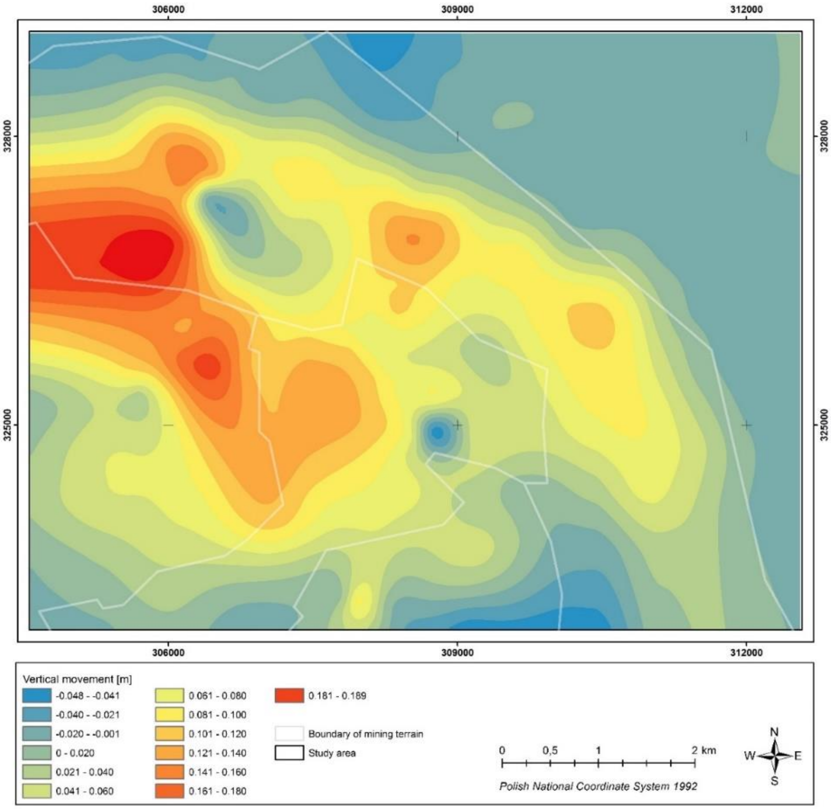

Fig. 11. Vertical movements in the Walbrzych Coal Mines in the 1992-2014 period [P3]

Effects of open-pit mining

At the same time, my research interests are focused on the studies on other spatial effects of mining on the surroundings using spatial statistics and multi-criteria analyses in GIS. This stage of research work, described in ([P7]), concerned the analysis of a spatial distribution of rock minerals mining, identification of mining concentration areas and changes in concentration of mining in time and in space, as well as evaluation of the impact of rock mineral quarrying on the surroundings in the example of the Lower Silesian province. Lower Silesia has the largest deposits of aggregates in Poland and is the largest manufacturer of aggregates. Intensive mining of rock minerals is connected to a number of negative effects on the surrounding environment and quality of life. To solve the research problem, I used the kernel density function, which is a non-parametric kernel density estimator proposed by Epenechinkov (1969) (3):

$$f_{\lambda}(x)=\frac{1}{n\lambda}\sum K_{0}\left(\frac{x-x_{i}}{\lambda}\right) \qquad (3)$$

where:

K_0 – is the kernel function,

λ – is the smoothing parameter that determines the range of neighbourhood and smoothing degree,

x – is the analysed variable,

n – is the sample size.

A square kernel function has the following form (4):

$$K_0(t) = \begin{cases} 0.75(1-t^2) & for\ |t| \le 1 \\ 0 & other\ cases \end{cases} \tag{4}$$

As a result of the application of the above function in GIS, I obtained surfaces representing the size of the discussed phenomenon per area unit (spatial variables). The modeled surface is matched with points representing the variable's values (the parameters are: position x, y, value of the variable in a given position, r search radius, unit of area). I determined the spatial changes in the distribution of concentrations of rock minerals mining in the analysed period (Fig. 12) on the basis of maps obtained as a result of calculations using map algebra operations (Fig. 13).

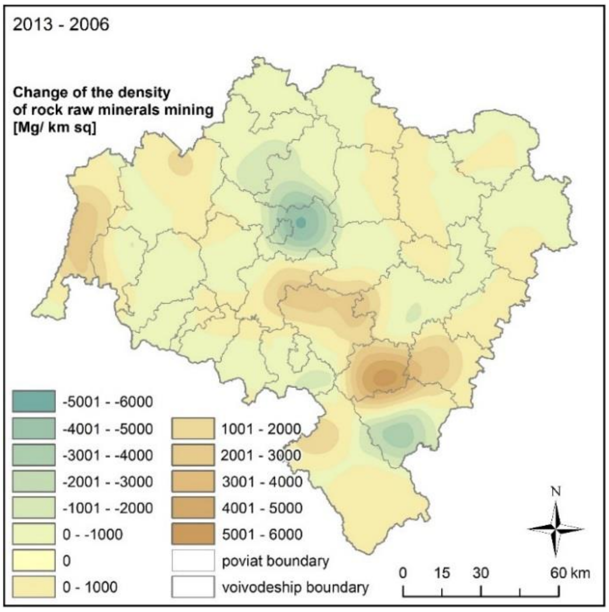

Fig. 12. Change of density of rock minerals mining in the 2006-2013 period

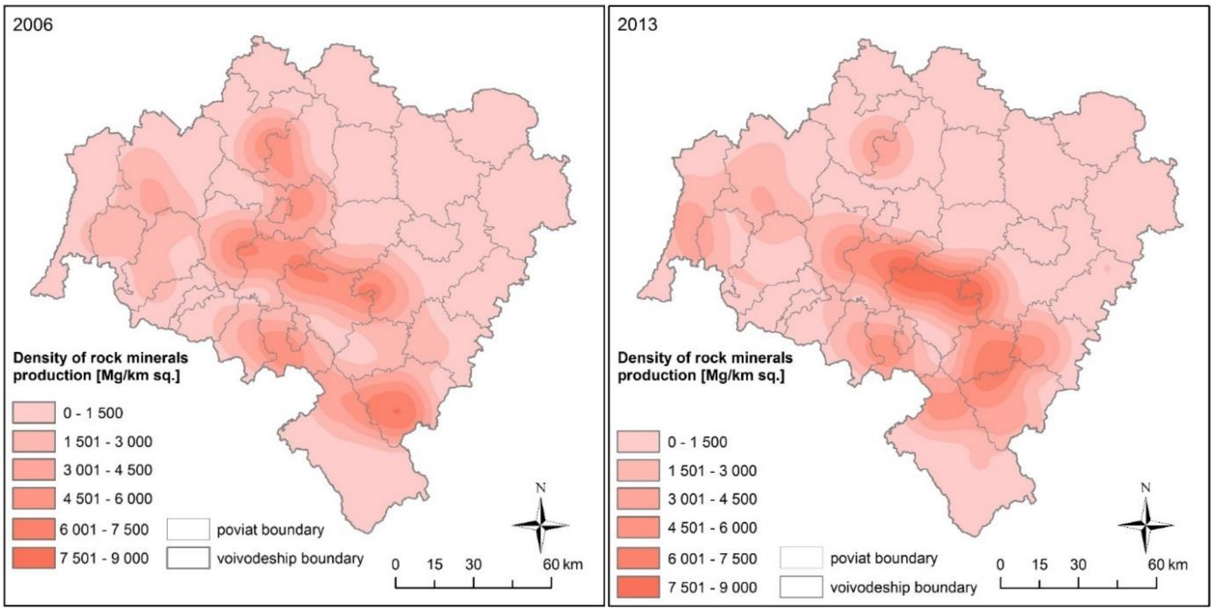

Fig. 13. Rock minerals mining density in year 2006 (left) and in year 2013 (right)

In the period up until 2013, i.e. the peak of mining, I found that the fields of concentration of the mineral production shifted in the north-eastern direction, I also found an intensification of excavation in traditional rock mining areas gathering groups of mining plants. Moreover, I observed the opening of single large quarries and growth of importance of production from large quaries. I also determined changes in the spatial density of excavation between the first (2006) and the last period (2013) of analysis with similar total production values in those periods. Those changes are the effect of closing and opening of mining plants, manifesting as areas of decrease and increase in rock material production while maintaining the role of traditional mining areas in the Lower Silesia.

In the studies, I have also identified sources of road transport flows, determined size of these flows and, based of proximity analysis, proposed alternative solution, i.e. shift of rock mineral road flows to rail transport. For this purpose I defined capacity of railway loading points for aggregates in relation to mines using road transport at a given distance. The research methodology, based on continuous representation of criteria in space (spatial variables), map algebra, and spatial statistic tools in geo-information systems allowed me to perform complex analyses of rock minerals mining on the surrounding space. The results of studies, including the evaluation of the effects of regional raw material management on the surroundings were used in documents determining the regional spatial policy (spatial development plan, development strategy) developed for the Self-Government of the Lower-Silesian Province.

Effects of large scale open-cast mining

In publication ([P2]), I described the results of studies on the effects of mining considered as a spatial conflict between areas of documented brown coal deposits and their potential open-pit excavation and other functions of the terrain. In order to solve the problem, I modified and combined the methods of the Analytical Hierarchy Process (AHP) introduced by Saaty (1980, 2008), as well as the Weighted Linear Combination (WLC) in GIS. Those methods are used e.g. in spatial analysis of location-related problems and belong to the group of Multi-Criteria Assessment (MCA) or Multi-Criteria Evaluation (MCE) (Malczewski, 2006; Drobne and Lisec, 2009). In the available literature on the subject, I did not find any examples of the approach to the solution of problems related to the evaluation of the effects of potential large-area deposit mining proposed by me. The Multi-Criteria Assessment methods allow for the assessment of complex, multi-dimensional decision-making problems concerning possible choices (in the discussed issue of designated purpose of areas). The procedure algorithm that I developed, combining both methods, involves the following: (i) identification of environmental and planning criteria of deposit accessibility, (ii) determination of the weight of accessibility criteria on the basis of the Analytical Hierarchy Process, (iii) development of single-factor maps of spatial representation of criteria, (iv) combination of standardised rasters (spatial variables in the model) representing criteria using the weighted average method (map algebra), (v) determination of spatial accessibility of the area of documented deposit for open-pit mining. I conducted the studies for one of the largest brown coal deposit areas in Poland, i.e. Legnica deposit in the Lower Silesian Province together with two other, smaller deposit areas - Ścinawa and Ruja. With the AHP method, it was possible to carry out systematic, quantitative assessments of criteria relevance by a group of expert, as well as to verify the coherence of such assessments. It involves the development of a hierarchical structure composed of several levels (aim, criteria, sub-criteria and variants). As a result of comparing pairs of criteria, a comparative scale is obtained. The comparisons may result from actual measurements or assessment scales reflecting the preferences. The preferences are described by relative grades expressed through numbers, usually from 1 to 9, where 1 means that the compared criteria are equally relevant and 9 means that the first of the compared criteria is much preferred in comparison with the other element. On the basis of such assessments, preference matrices are construed taking into consideration the following principles: a given matrix element is self-equivalent, i.e. equal to 1 and the value of the grade of element a with regard to element b is the inverted grade of element b with regard to element a (5):

$$\begin{array}{c|ccc} & A_1 & \cdots & A_n \\ \hline A_1 & \frac{w_1}{w_1} & \cdots & \frac{w_n}{w_1} \\ \vdots & \vdots & \ddots & \vdots \\ A_n & \frac{w_n}{w_1} & \cdots & \frac{w_n}{w_n} \end{array} \tag{5}$$

Then, the values of normalised matrix and priority vectors showing the weights of individual elements (criteria) are determined. The final stage is to check the coherence of the obtained criteria weights ([P2]). The WLC method uses criteria weights to determine spatial occurrence of all the analysed factors. At the first stage, single-factor maps of the analysed criteria (spatial variables) are developed and standardised according to the scale representing their usefulness. The final grade is obtained by multiplying the weight set to each of the criteria normalised by the criterion value and summing up the products for all criteria maps (6):

$$S = \sum_{i=1}^{n} w_i \, k_i \prod c_j \tag{6}$$

where:
S – value of the raster cell representing the result,
w_i – criterion weight i = 1, …, n,
k – criterion value for a given raster cell i = 1, … n,
n – number of criteria,
c_j – restriction, j = 1, … m (in the case of taking into consideration excluding criteria in the assessment=,
Π - logical product (conjunction).

Table 2 presents the criteria identified in the study (described in ([P2])) and criteria weights I obtained on the basis of grades selected by an interdisciplinary group of experts. Value λ is a mean value of the priority vector used for calculation of the coherence index, which in my case was equal to 0.03 (the permissible value is 0.10). The assessment of experts' grades revealed that the most significant are the following criteria: 12 - environmental protection areas (0.193), 15 - cultural heritage areas (0.142) and 8 - underground water areas (0.095), 7 - surface water areas (0.087) and 1- built-up areas (0.093).

Table 2. The comparison matrix ([P2])

crit.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	waga	λ
1	0,08	0,09	0,11	0,13	0,07	0,11	0,05	0,06	0,11	0,08	0,06	0,07	0,16	0,11	0,12	**0,093**	**16,009**
2	0,03	0,03	0,06	0,03	0,04	0,05	0,03	0,03	0,03	0,07	0,03	0,03	0,02	0,03	0,03	**0,035**	**15,453**
3	0,01	0,01	0,02	0,01	0,01	0,02	0,02	0,02	0,01	0,02	0,01	0,03	0,02	0,02	0,03	**0,018**	**15,525**
4	0,02	0,03	0,07	0,03	0,02	0,05	0,02	0,03	0,02	0,06	0,03	0,03	0,03	0,03	0,03	**0,033**	**15,403**
5	0,03	0,02	0,04	0,04	0,02	0,01	0,02	0,03	0,01	0,03	0,02	0,03	0,02	0,02	0,03	**0,025**	**15,648**
6	0,02	0,02	0,02	0,02	0,04	0,02	0,02	0,03	0,02	0,03	0,02	0,03	0,02	0,02	0,03	**0,023**	**15,549**
7	0,13	0,09	0,08	0,11	0,13	0,10	0,08	0,05	0,06	0,09	0,06	0,12	0,05	0,08	0,08	**0,087**	**15,764**
8	0,13	0,10	0,08	0,10	0,09	0,09	0,17	0,09	0,13	0,09	0,08	0,10	0,04	0,04	0,09	**0,095**	**15,812**
9	0,03	0,05	0,06	0,05	0,07	0,06	0,06	0,03	0,04	0,09	0,05	0,04	0,03	0,04	0,04	**0,049**	**15,562**
10	0,02	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,01	0,02	0,02	0,03	0,02	0,01	0,02	**0,015**	**15,616**
11	0,06	0,05	0,07	0,05	0,07	0,06	0,06	0,05	0,04	0,05	0,04	0,04	0,02	0,02	0,04	**0,047**	**15,602**
12	0,25	0,18	0,13	0,17	0,16	0,15	0,14	0,18	0,23	0,13	0,20	0,20	0,27	0,34	0,17	**0,193**	**16,216**
13	0,03	0,10	0,07	0,07	0,07	0,07	0,10	0,13	0,08	0,07	0,13	0,05	0,06	0,05	0,06	**0,076**	**15,886**
14	0,04	0,06	0,07	0,06	0,07	0,07	0,06	0,12	0,06	0,07	0,11	0,03	0,07	0,06	0,06	**0,067**	**15,855**
15	0,11	0,16	0,11	0,14	0,12	0,12	0,16	0,15	0,14	0,11	0,16	0,18	0,17	0,14	0,16	**0,142**	**15,931**
Sum	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,000	-

1 – built up areas, 2 – road infrastructure (main), 3 – road infrastructure (secondary), 4 – railway infrastructure, 5 – power infrastructure, 6 – gas network, 7 – surface waters, 8 – underground waters, 9 – arable land (highest quality), 10 – arable land (other), 11 – forests, 12 – environmental protection areas, 13 – valuable nature areas, 14 – ecological corridors, 15 – cultural heritage.

For each criterion, I prepared a standardised raster map with a cell resolution of 50 m (spatial variables in the model). The maps were reclassified to the value of 1 - criterion is present, 0 - criterion is not present. Then, as a result of map algebra operations, I developed an outcome map of potential conflicts in open-pit mining according to WLC methodology. The theoretical maximum pixel value of an outcome map is 1. This value represents co-occurrence of all the analysed criteria in space. The statistics obtained for Legnica deposit area are as follows: the maximum value of a raster cell equals 0.55, mean value equals 0.10 and standard deviation equals 0.07. On the basis of those statistics and a histogram of values of the outcome map, I proposed two classifications of accessibility of the area of the analysed deposit. The first one, divided into two categories, describes the most inaccessible areas with values above the average, i.e. 0.12-0.55, as well as the least inaccessible areas with values lower than and equal to the obtained average value, i.e. 0.11. The second classification is based on the Jenks' natural breaks algorithm (1967). The classification covers three classes: the most inaccessible areas (values from 0.25 to 0.55), relatively inaccessible areas (values from 0.12 to 0.24), as well as the least inaccessible areas (values up to 0.11). The last category corresponds to the category obtained in the first classification method. The results in a graphic form are presented in Fig. 14.

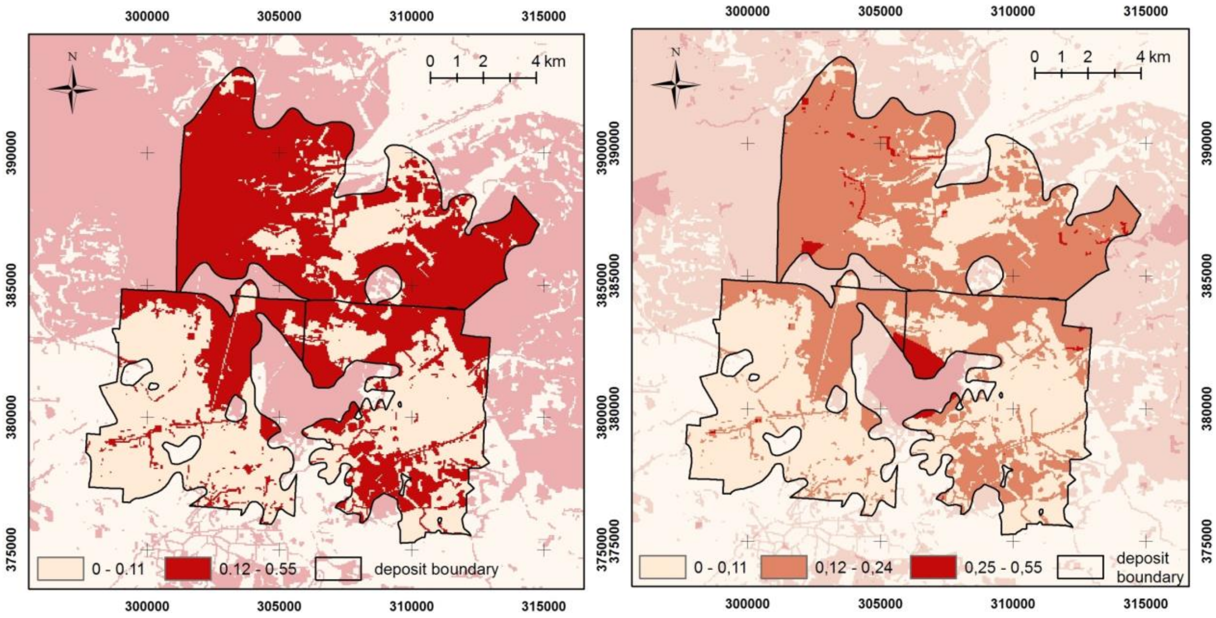

Fig. 14. Results of the multicriteria analysis of accessibility of brown coal deposit classified into two classes (left) and three classes (right) [P2]

I obtained a quantitative assessment and spatial representation of the accessibility of the analysed deposit in terms of the discussed criteria types. I determined, in terms of identified and classified (with regard to relevance) planning and environmental criteria, the most and least conflicting areas for potential open-pit mining within the boundaries of the documented brown coal deposits. The results show that for the analysed spatial and functional development criteria, 53.6% of the area of Legnica deposit (W, E and N fields together) is inaccessible and the remaining 46.4% is potentially inaccessible. Analysing individual deposit areas, the most difficult to develop is N field (79.3% of its area is inaccessible) and the best area for the development is W field with 28.8% of inaccessible area.

To sum up, the method of spatial analysis of accessibility of documented, undeveloped deposits established and tested by me allows for quantitative assessment and spatial representation of accessibility in terms of the discussed criteria types. In order to take into consideration the restrictions and barriers for development, it is possible to consider Boole's operators in the method and to introduce fuzzy sets operators in the analyses in order to compensate for its continuous nature. Despite the limitations, such as the possibility of compensation for one criterion by other co-existing criteria, the methodology is a good indicator of the problem of investment conflicts and simultaneously means for the support of spatial development policy and raw mineral management, providing quantitative assessments of decision-making problems related to spatial planning.

D. Summary

In my summary of professional accomplishments, I presented a description of studies concerning Spatial GIS analyses in studies on the effects of mining activity on the surroundings. I consider that the most important accomplishments of my research work documented in the presented series of thematically related publications in the discipline of mining and engineering geology, specialization in mine surveying, are as follows:

- proving, on the basis of theoretical and experimental works on various mining objects, the applicability of the proposed approach based on representation of variables as continuous fields of values and GIS spatial analysis functions in studies of surface deformations caused by mining,
- enhancing methods of analysis of surface deformation on mining grounds with application of spatial statistics and map algebra in GIS,
- proving that GIS methods are effective for precise spatio-temporal description of surface deformation in areas under the influence of mining carried out in complicated geological and mining conditions in comparison to commonly employed methods,
- calculating the indexes of surface deformation that developed in the result of simultaneous exploitation of evaporites and shale gas and in the conditions of limited survey data,
- proving that there is no effect of simultaneous exploitation of many deposits (various evaporites and shale gas) on the condition of buildings on the surface,
- determining historic deformations of mining area surface in Wałbrzych Coal Basin (*Wałbrzyskie Zagłębie Węglowe*) over the period of the last 123 years of exploitation and proving that those deformations had a more varied character than the model resulting from predictions based on Knothe's theory,
- proving the spatial variability of the phenomenon of secondary deformations in the post-mining period in Wałbrzych Coal Basin (*Wałbrzyskie Zagłębie Węglowe*) and explaining the cause of such a variability,
- developing digital knowledge database on done mining of black coal in Wałbrzych,
- developing my own system of information on mining deformations, whose functions and computational tools support research and predictions concerning surface deformation of areas subjected to underground mining,
- developing and implementing an integrated system for the monitoring and analysis of surface deformation using geodesic surveys, numeric modeling (FEM) and geo-information systems in the condition of changing the mining system of iron ore deposits exploitation (Kvannevann mine),
- proving, on the basis of realised research work, that the methodology of multi-criteria analyses in Geographic Information Systems in studies on other spatial effects of mining on the surroundings is effective,
- determining the areas of documented deposits potentially available for development using open-pit methods on the basis of the results of analyses conducted with the combination of Analytical Hierarchy Process and weighted linear combination methods in GIS,
- calculating, on the case of Lower Silesia Province, the spatial distribution of density of rock mineral mining and describing the changes in concentration of mining in space and in time, together with explaining the causes of observed changes,
- Applying the research results in planning practice by translating them into provisions of documents determining the spatial development policy in the Lower Silesian province.

4.4. Description of other scientific achievements

A. Scientific achievements before being conferred the doctoral degree

In the secondary school, I attended the science-oriented class and participated in the geographical club. During my master's studies at the Mining Faculty at the Wrocław University of Technology, I participated in the European Tempus student exchange program and spent a semester at the University of Glamorgan in Great Britain. During that stay, I got interested in the possibilities of the satellite positioning and navigation system (NAVSTAR-GPS) that had been developing at that time. The result of such interest was my master's thesis entitled "*Point positioning with RTK DGPS satellite technique for the needs of opencast mining*" that was written after my return to my home university. The results of the studies carried out within that work were presented by me during the 11th International Congress of the International Society for Mine Surveying that was held in Cracow on 4-9 September 2000. Earlier in 1998, I was awarded the prize of the Dean of the Mining Faculty for very excellent educational results.

In October 1999, I commenced postgraduate studies at the Mining Faculty at the Wrocław University of Technology. I dealt with the studies in the area of the impact of the present-day tectonic activity of the surface layers of the Earth's crust on the safety of man-made water reservoirs. In particular, I dealt with the issues related to the observation of deformations of rock mass surface in the control and measurement networks in the area of such reservoirs with taking into account the aspect of geological structure and modelling of deformations of rock mass in the proximity of water reservoirs with the use of numerical technique of finite element method (FEM). The results of the studies were gathered in the doctoral dissertation entitled "*Analysis and interpretation of deformations of the surface layer of the Earth's crust in the proximity of designed water reservoir*", which was awarded a distinction by the Council of the Faculty of Mining on 29 September 2003. On the basis of the analysis covering the results of repeated surveying, satellite and gravimetric measurements, I confirmed the contemporary movements of the surface layer of the Earth's crust in geological structures in the proximity of the planned Kamieniec water reservoir. I also developed the methodology of monitoring such type of objects. With the use of the finite element method, I prepared the prediction of the impact of the designed water reservoir on the surrounding rock mass and designed the control and measurement system to monitor the security and safety level of the planned dam.

During my doctoral studies, I got interested in Geographic Information Systems (GIS) as the environment supporting scientific research, e.g. in the scope of collecting and managing different spatial datasets and in the scope of visualisation of data in two- and three-dimensional space. The most of all, I got interested in the analytical possibilities of geographic information systems. Therefore, in 2002, I started my postgraduate studies in the field of geographic information systems and I completed them in 2004.

During that time (1 February 2001 - 29 September 2003), I received and used the supervisor research grant awarded by the Committee of Scientific Research (KBN), which gave me the possibility - among other things - of carrying out two campaigns of satellite GPS measurements on geodynamic research area in the proximity of the object of research and of analysing the movements of measurement points together with the results of earlier measurements.

In the period before being conferred the doctoral degree, I participated in six conferences, including two international ones. My presentations were twice awarded the distinctions at the conferences of doctoral students at the Mining Faculty at the Wrocław University of Technology twice (the 1st prize in 2002, and the 2nd prize in 2003). My scientific achievements in the period of doctoral studies cover nine items:

- 2 publications in materials of national conferences with international impact, written in co-authorship (in English),
- 4 publications in materials for national conferences, of which 2 with single authorship,
- 1 chapter in a book with international distribution (written in co-authorship),
- 2 chapters in books with national distribution (written in co-authorship),

In addition, I am a co-author of 3 unpublished scientific works (reports). The detailed description of the achievements in that period is included in **Point 5.2 of the Appendix No. 5** to the documentation.

Since the beginning of my doctoral studies, I have been involved in the activities of the students' scientific and research club interested in GIS. I co-organized teaching trips to geodynamic research areas in Lower Silesia.

Within the obligatory teaching hours, I was giving the laboratory classes in the following subjects: Computer Science, Introduction to GPS and Satellite Positioning Systems. In order to develop my scientific and teaching skills and abilities, I attended the classes educating in the scope of scientific speech forms, artificial intelligence methods in problem solution, finite element method, and other.

B. Scientific achievements after being conferred the doctoral degree

My scientific research activity after obtaining the degree of doctor of technical sciences involved several important areas of research having a large impact on the development of the field of mining and engineering geology. The research work was related to the following main issues:

B1. Application of satellite positioning and Geographic Information Systems and obtaining and analysing multi-thematic spatial data

a. Development of the methodology of obtaining and updating spatial and descriptive information for the purposes of field mapping and inventory of geotopes (elements of inanimate nature conveying comprehensible information on the development of earth crust or life on Earth (Look, 1996)) in the example of the tourist project - making the Polish section of the planned "Łuk Mużakowa" geo-park available to the tourists (Blachowski and Koźma, 2005).

b. Application of satellite positioning in obtaining spatial and bathymetric data for the purposes of design works related e.g. to remediation of post-mining areas (Blachowski and Mizera, 2005).

c. Development of the methodology of obtaining spatial data using mobile GIS (GIS and satellite GNSS measurements) in field inventory and design of coherent, thematic cycling routes, as well as the methodology of spatial analyses for automatic determination of the difficulty level of cycling routes depending on terrain conditions (Blachowski and Głowacki, 2005; Blachowski, 2006). The methodology was applied to set the St. James' cycling route in the Lower Silesia under Via Regia Plus project entitled *„Sustainable Mobility and Regional Cooperation along the Pan-European Transport Corridor III”*.

d. Application of advanced mobile geo-information systems for the systemic monitoring of mining area environment and to develop the models for the development of post-industrial areas - research carried out under a designated support of the Ministry of Science and Higher Education (projects No. 342797 - 2006 and No. 342889 – 2007).

B2. Modeling and analysis of spatial data related to Earth resources management in Geographic Information Systems

a. Development and testing of spatial analysis algorithms supporting the process of rock minerals management, including modification of the valuation methodology (Nieć and Radwanek-Bąk, 2011) and development of tools for automatic valuation of undeveloped rock mineral deposits in Geographical Information Systems.
b. Development of a structure of geo-information systems concerning rock mineral deposits for the support of decision-making processes related to the management of raw mineral resources. A practical effect of the performed research and development works are Geographic Information Systems containing data on rock minerals for three counties in the Lower Silesian province: Kłodzko county, Świdnik county and Wrocław county, implemented in the Spatial Information Systems of the two latter ones. The results of those works, carried out under the project entitled *"Technological strategies and scenarios for the development and use of rock material deposits"* implemented in the years 2009-2013 under the Innovative Economy Operational Programme and coordinated by the Poltegor Institute of Open-pit Mining in Wrocław, were published in the series of co-authorship monographs and co-authorship publications listed in the research portfolio (**point 5.2 of the Appendix No 5 to the documentation**).
c. Analysis of possible use of Free and Open Source Software (FOSS) GIS to develop procedures supporting valuation of raw material deposits and multi-criteria analysis of availability of deposits for use. Studies carried out in the example of Kłodzko county (Blachowski and Książkiewicz, 2013; List B of the MoSaHE 6 points; Blachowski and Masłowska, 2015; List B of the MoSaHE 7 points).

B3. Development of geo-information systems and interactive map applications

a. Development of the structure and making a GIS database of mining activity in the Walbrzych Coal Basin (Wałbrzyskie Zagłębie Węglowe) together with spatial (3D) models of underground and surface infrastructure on the basis of archive cartographic materials, maps and plans of underground excavation sites, geological and mining documentations, as well as other materials. Development of a knowledge database concerning over two hundred years history of black coal mining in the Walbrzych Black Coal Mines (Wałbrzyskie Kopalnie Węgla Kamiennego) (since the beginning of the 19th century) together with the ability for the analysis and geo-visualisation of historic blueprints of mining plants, exploitation methods used and the progress of exploitation in geo-information system (Blachowski, 2008; Blachowski and Stefaniak, 2012, Blachowski and Stefaniak 2013; List B of the MoSaHE, 5 points).
b. Recording and preserving information on the legacy of mining industry and developing a method of dissemination thereof in the Internet. A project of a geo-information system and an interactive map application concerning former mining facilities of the "Julia" mine in Wałbrzych. (Blachowski and Nowacka, 2011; List B of the MoSaHE, 9 points).

c. Making a pilot provincial spatial information node for the purposes of dissemination of planning information concerning the functional area of Wrocław and the Lower Silesian province in a free and open source GIS software environment (Blachowski et al., 2008; Malczewski et al., 2010; List B of the MoSaHE 6 points).
d. As part of the working group led by me under the project entitled „*Razem dla Pogranicza*" (Together for the Borderland) (Poland - Saxon Cross-Border Cooperation Operational Programme 2007-2013) - initiation of analyses regarding cross-border access to geodetic data portals in Saxony and Lower Silesia, resulting in harmonisation and interoperability of spatial data.

B4. Application of multi-criteria spatial GIS analyses in studies on accessibility of terrains for the support of decision-making processes in the planning of rational spatial development.

a. Performing an analysis of locations based on the AHP - Analytical Hierarchy Process and weighted linear combination (WLC) in GIS with the participation of an interdisciplinary group of experts. Carrying out studies for Wrocław Functional Area in order to determine areas suitable for new residential development with regard to identified criteria groups (i.e. availability of public transport, technical infrastructure, public services and commercial services, as well as ecophysiographic usefulness) and limitations connected with such areas (Blachowski et al., 2017; List B of the MoSaHE, 10 points).
b. Participation in studies on environmental and social conditions of the exploitation of the documented "Legnica" brown coal deposit based on the method of integration of independent experts' assessments and opinions of stakeholders for the purpose of objectivisation of arguments in the process of making planning and administrative decisions (Malewski et al., 2008).
c. Participation in studies on the concepts of sustainable utilisation of post-mining areas in the area of power transformation using the methodology of integrated planning of utilisation of post-excavation areas for renewable power industry (under the project entitled "*Razem dla Pogranicza*").
d. Carrying out analyses of planning conditions based on the findings of studies on the conditions and trends in spatial planning in communes, as well as coverage of the area of undeveloped deposits of brown coal with local spatial development plans. Analysis of the possible use of the Analytical Hierarchy Process for objective and quantitative determination of relevance of conditions in the generation of conflicts with protection and potential exploitation of brown coal deposits (Blachowski, 2014; IF 0.540, List A of the MoSaHE 15 points).
e. Studies on the usefulness of land for the construction of wind power plants using the methodology of multi-criteria raster analyses in GIS in the example of Prusice commune in the Lower Silesian province (Szurek et al., 2014; List B of the MoSaHE 5 points) and the analysis of spatial distribution of the existing and planned investments in the Lower Silesian province (Blachowski et al., 2010).

B5. Studies on present-day geodynamics and its impact on mining areas

a. Analysis of the impact of geodynamics of the surface layers of the Earth crust in mining areas, as well as design of survey networks for the purposes of geodynamic surveys in mining areas. Development of a concept for a research geodynamic network in the area of Wałbrzych together with pilot GNSS measurements (Blachowski et al., 2009; IF 0.275, List A of the MoSaHE 9 points; Blachowski et al., 2010; IF 0.452, List A of the MoSaHE 10 points).

B6. Application of satellite radar interferometry for the recording of surface displacements in mining and post-mining areas

a. Review of possible applications of satellite radar interferometry in the analysis of the condition of the surface of areas of former underground mining activity (Blachowski and Milczarek, 2007).
b. Application of the Permanent Scatterers satellite interferometry technique (PSInSAR) in the analysis of occurrence and dynamics of surface displacements in former mining areas in Wałbrzych in the post-exploitation period (2002-2009). Determination of positive vertical displacements (in LOS - Line of Sight) up to +6mm/year with decreasing trend. In some areas, stabilisation of the surface and its further subsidence in the most recent analysed years has been observed (Milczarek and Blachowski, 2016; Milczarek et al., 2017; IF 0.561 List A of the MoSaHE 20 points).

   Complementary use of data sources originating from sensors placed on Envisat and Sentinel satellites, PSInSAR and SBAS data processing technologies (Feretti, 2014), as well as spatial analyses and spatial statistics function in GIS is a research problem I have been dealing with at present. My research plans in the nearest future include a comprehensive description of the stages of occurrence of secondary deformations in post-mining areas, as well as studies on the surface deformations in the vicinity of artificial water reservoirs and dams. For this purpose, I have prepared and received a research grant from the European Space Agency (ESA) entitled *„Studies of earth crust surface movements in the vicinity of large man-made water reservoirs (Zambezi River Valley)*", allowing me to obtain interferometric data for the research on surface activity of the Earth crust in the region of the Great Dyke geological structure in Zimbabwe, as well as to develop models describing surface deformations in the area of large water reservoirs located in Zambezi River valley. I have also been conducting a project funded from the designated subsidy of the Ministry of Science and Higher Education entitled *"Studies on the activity of area surface in the vicinity of large water reservoirs using Geographic Information Technology and Satellite Interferometry".*

The cited works, as well as the list of all the other research publications after obtaining the degree of doctor of technical sciences are listed in **Point 5.2 of Attachment No 5**.

4.5 Literature

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4.6. Summary of scientific achievements

The results of my research work include scientific publications in JCR indexed journals, journals on the MoSaHE (MNiSW) list, papers in conference proceedings and other works. Summary of scientific achievements before and after obtaining the doctoral degree is given in Table 3, including h-index and number of citations (Table 4).

Table 3. Summary of scientific achievements

	Before Ph.D.	After Ph.D.	Together
Publications in JCR	-	13	**13**
Monographs and publications not included in JCR	3	44	**47**
Peer-reviewed papers in conference proceedings	6	18	**24**
Collective works, reports	3	16	**19**
Popular science publications	-	6	**6**
Presentations at international and domestic conferences	6	48	**54**
Participation in research projects	2	18	**20**
International and national awards for scientific activities	4	13	**17**
Total Impact Factor	-	10,93	**10,93**
Total number of MSHE (MNiSW) points	5	446	**451**

Table 4. Number of citations and *h* Index (Hirsch) excluding self-citations

	Web of Science	Google Scholar
Number of citations	32	80
h Index (Hirsch)	3	5

4.7. Activities in the field of education

My teaching achievements may be divided into the following areas of activity. The first of them includes teaching activities in the form of lectures, laboratory classes and project classes, and seminars. They include mainly the subjects in the scope of geographic information systems and global navigation satellite systems (GNSS). I teach at the Faculty of Geoengineering, Mining and Geology (former Faculty of Mining) at the Wrocław University of Science and Technology since 2000. At the beginning, within my doctoral studies (up to 2003), and then as an assistant lecturer and lecturer at full-time and part-time studies in the field of mining and geology, and full-time studies in the field of geodesy and cartography, and at postgraduate studies in the area of geographic information systems.

In the discussed period, I was giving classes within 18 subjects (without taking into account the postgraduate studies), of which 12 in a form of lectures and 2 subjects were taught in English for the participants of international studies leading to a master's degree. For the purposes of the teaching activities pursued by me, I developed proprietary content and teaching materials for 10 courses (lecture and laboratory class) including the aforementioned 2 courses taught in English. The summary of subjects taught be me is included in **point 6.6 of Appendix No. 6** to the documentation. During the classes and lectures given, I pay particular attention to getting the students interested in GIS and GNSS through e.g. showing my achievements and experience gained within the completed research, trainings, traineeships and scholarships and participation in conferences and workshops.

Till now, I have been the supervisor of 95 diploma papers, of which: 24 master's theses, 30 engineer's projects and 41 diploma theses at postgraduate studies in the area of geographic information systems. Three diploma theses were written in the English language under my supervision. Five theses have been awarded a prize. Two of the diploma candidates supervised by me carry out the research within the doctoral studies, and the third one - after their completion - continues the scientific work at the Faculty of Geoengineering, Mining and Geology. Since 19 June 2013, pursuant to the resolution adopted by the Council of the Faculty of Geoengineering, Mining and Geology, I am the auxiliary supervisor in the registration and conferment procedure for a doctoral degree of Aneta Barańska-Buslik, MSc, entitled "Method of assessment of brown coal deposits with the use of GIS tools".

My teaching activities are expanded with the participation in the development of curricula for new fields and specialities of study. For the first time, I had such a possibility at the beginning of my professional career at the Wrocław University of Science and Technology when I participated in the preparation of the curriculum for the speciality of geoinformatics in the study field of mining and geology. Afterwards, I was responsible for and coordinated the preparation of the curriculum (including the effects of education in the study field, studies plan and programme, and other documents) of a new study field that was popular with university candidates, that is geodesy and cartography. It was launched at the Faculty of Geoengineering, Mining and Geology within full-time studies for the bachelor degree in the academic year of 2011/2012. I also coordinated the development of the curriculum for a new geoinformatics specialisation for the full-time studies for the master degree (the study field of mining and geology), which was relaunched from the spring semester in the academic year of 2014/2015.

The next area of educational activity that I would like to mention is the supervision of the GIS student's Scientific and Research Club at the Faculty of Geoengineering, Mining and Geology. I strive to develop the student's interest in geographic information systems, e.g. through supporting the implementation of students' scientific projects and organisation of different events such as e.g. the Surveyor's Day, the GIS Day, GeoMay Hike, and other. This year I started scientific cooperation with the TabIe Mountains National Park. I also cooperate with the GIS section of the Eko-Instytut Scientific Club at the Faculty of Environmental Engineering. I also get a lot of satisfaction from classes and presentations organised several times in a year in different forms for students, pupils from middle and primary schools which are aimed at popularising science. In my opinion, the most interesting and the most popular ones include the presentations within the Lower Silesian Science Festival. Their objective is to familiarise the participants with the issues related to geographic information systems and satellite positioning and navigation. I supervise Erasmus programme students from abroad and also participate in the organisation of vocational trainings for students, as well as trips and teaching visits, e.g. the visits by students from the Faculty of Spatial Information of Hochschule für Technik und Wirtschaft in Dresden (Germany).

The detailed information about the teaching and popularisation activities carried out by me is included in points **6.6-6.8 and 6.15 of Appendix No. 6 to the documentation**.

4.8. Organisational activities

In the period of my employment at the Faculty of Geoengineering, Mining and Geology, and in addition to scientific, research and teaching activities, I fulfilled different organisational functions connected both with education and management. The most important of them include:

- performing the duties of the head of the Geodesy and Geoinformatics Division (1.10.2010-30.09.2011),
- head of the Geodesy and Geoinformatics Division (1.10.2011 – 31.12.2014),
- performing the duties of the head of the Faculty Division of Geodesy and Geoinformatics (1.01.2015 – 20.10.2016),
- deputy head the Geodesy and Geoinformatics Division (1.11.2016 – presently),
  My scope of responsibilities includes managing the team of over a dozen scientific-research and teaching employees, planning and supervising the development of the research activities of the Unit, including the expanding the staff possibilities in connection with the expansion of education and research-development activities of the Faculty with geodesy and cartography. In this time the number of scientific and teaching staff increased from 7 to 15 people.
- deputy director of the Institute of Mining Engineering for scientific research and cooperation with industry (1.10.2012 – 31.12.2014),
  My scope of duties included being responsible for e.g. research and development cooperation of the Institute with enterprises and scientific and research units, developing the competence of the Institute in the scope of orders for industry and administration, controlling the research and development projects carried out within the Unit, taking care of adequate distribution of

and accounting for the funds granted within the designated subsidy for the scientific research carried out by the employees of the Institute,

- member of the disciplinary board for doctoral students in the term from 2008 to 2012,
  Within the works of the board, I participated - as a defence - in the disciplinary proceedings concerning the plagiarism in a doctoral dissertation, to give an example,
- member of the Curriculum Committee for Education Quality Assessment and Assurance in the study field of Geodesy and Cartography and the Committee for the geoinformatics specialization in the study field of *mining and geology*,
  Within the works carried out by the Committee and as the head of the Geodesy and Geoinformatics Division, I coordinated the works on the preparation and implementation of curricula in the study field of geodesy and cartography and in the specialisation of geoinformatics (the study field of mining and geology) in accordance with the National Qualification Frameworks. I also fulfil the function of the supervisor of the study field of geodesy and cartography and - among other things - I provided substantive and organisational support for the deputy dean for teaching, dean's proxy for trainings, and dean's proxy for international cooperation,
- head of the Division's laboratory of GIS and photogrammetry,
- member of the Scientific Council of the Institute of Mining Engineering in the term from 1.10.2010 to 31.12.2014,
- member of the Council of Faculty of Geoengineering, Mining and Geology in the term from 2008 to 2012 (from 28.04.2010 - as a result of supplementary elections),
- member of the Council of Faculty of Geoengineering, Mining and Geology in the term from 2012 to 2016,
- member of the Council of Faculty of Geoengineering, Mining and Geology in the term from 2016 to 2020,
- member of the Faculty Committee for Observation of Teaching Practice (since 2012),
- member of the Faculty Committee for Statutory Subsidy (since 11.03.2015),
- member of the Faculty Committee for Scientific Personnel Development (since 10.06.2015),
- member of the Faculty Electoral College in the term 2016-2020,
- member of the examination board at full-time studies for the first degree in the study field of *mining and geology*, and member of the examination board at full-time studies for the first degree in the study field of *geodesy and cartography*.

I carry out such organisational activities as membership in scientific associations and councils also outside my home University. Among other things, I am:

- chairman and one of the founders of the Lower Silesian Commission of the Polish Association for Spatial Information (PASI),
- Member of the Polish Commission of the International Society for Mine Surveying (PK ISM),
- Member of the Commission 1: Education, Legal Issues, Web-Presentation, History, International Society for Mine Surveying,
- Member of the Commission 4: Rock and Ground Movements Subsidence Damages, International Society for Mine Surveying.

The remaining scope of my organisational activities is presented in **points 6.2-6.5 of Appendix No. 6** to the documentation, and the information about the participation in expert teams and competition juries and the reviewing of projects and publications is included in **points 6.10-6.13**.